Water Operations and
Technical Support Program

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Stream Management – Concepts and Methods in Stream Protection and Restoration

By J. Craig Fischenich
Environmental Laboratory
US Army Waterways Experiment Station
3909 Halls Ferry Rd., Vicksburg, MS 39180-6199

Hollis Allen
Environmental Laboratory
US Army Waterways Experiment Station
3909 Halls Ferry Rd., Vicksburg, MS 39180-6199

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Monitored by Environmental Laboratory
US Army Waterways Experiment Station
3909 Halls Ferry Rd., Vicksburg, MS 39180-6199

Foreword

By Jim Herrington and Presley Hatcher, US Army Corps of Engineers, Ft. Worth

Stream modification projects associated with residential, commercial, and industrial development on mostly headwater streams have raised concerns in developing metropolitan areas in Texas, such as Dallas/Fort Worth, San Antonio, Austin, and Tyler/Longview/ Marshall. These projects result in individual and cumulative impacts to the aquatic ecosystem, including water quality degradation and aquatic and riparian habitat destruction, and in many cases do not solve, but only transfer, the problems they are intended to address (erosion control, flood control, etc.). Many cities also have drainage ordinances that require developers to replace natural headwaters streams with buried conduits or with straightened, sometimes hard-surfaced, channels for easier maintenance.

The Fort Worth District is experiencing problems and delays in evaluating numerous permit applications because of the lack of a good framework for evaluating the impacts of these types of projects and the lack of good guidance for better watershed planning in the state. To address this problem, the district is working with the Waterways Experiment Station, through the Water Operations Technical Support (WOTS) program, federal and state resource agencies, and local governmental and planning authorities to develop a stream management education program. The goals of the program are to provide better protection for the aquatic environment through avoidance or more environmentally-acceptable projects, while rendering fair and reasonable decisions, and providing for increased efficiency for all parties involved in the Regulatory Program.

The program is a partnering effort among the above entities and consists of: (1) written guidance for stream management focusing on avoiding adverse impacts when practicable and implementing more aquatic ecosystem-friendly projects when avoidance is not practicable; (2) workshops for local governments, developers and consultants to present and explain the guidance and respond to questions about environmentally-sound stream management; and (3) demonstration projects to encourage practical applications of techniques presented in the guidance.

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Preface

This report was prepared by personnel of the Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES), as part of the Water Operations Technical Support Program (WOTS). The WOTS is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the WES EL. Drs. John Barko and Robert Gunkel, EL, WES, are the WOTS Program Managers.

The study was performed under the direct supervision of Mr. Norman Francingues, Chief, EED and Dr. John Keeley, Acting Director, EL. COL Robbin Cababa, EN, was Commander and Director of WES.

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About the Authors

J. Craig Fischenich is a research civil engineer at the U.S. Army Engineer Waterways Experiment Station (WES). He holds bachelor and Master of Science degrees, respectively, in Civil and Environmental Engineering from South Dakota School of Mines and Technology, and a PhD in Hydraulics from Colorado State University. His research has focused on stream and riparian restoration, erosion control, and flood damage reduction.

Hollis H. Allen is an ecologist at the U.S. Army Engineer Waterways Experiment Station (WES). He holds bachelor and Master of Science degrees, respectively, in Forestry and Forest Ecology from Oklahoma State and Oregon State Universities. His research has focused on riparian habitat restoration using bioengineering and other methods.

Conversion Factors
Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.0283	cubic meters
feet	0.3048	meters
miles (US statue)	1.6093	kilometers
inches	25.40	millimeters
square feet	0.0929	square meters
pounds (mass)	0.4536	kilograms
pounds (force per square foot)	47.88	Pascals
acres	4046.9	square meters

1 Introduction

Background

Based on discussions with the Fort Worth District of the U.S. Army Corps of Engineers (Corps) in late 1997, we set out to write a brief guidance document for environmentally acceptable stream modification, with a focus on streambank stabilization. The Corps and other agencies responsible for reviewing these activities through the Corps Regulatory Program have long been concerned about these activities because of their potential to cause significant stream and riparian degradation. In April 1998, the Corps hosted a meeting to discuss the development of a guidance document as one element of a strategy to better address permit applications for proposed stream modification projects. During the meeting, participants requested that the guidance document and the proposed workshops address good overall stream management principles as well as recommended in-stream treatment measures.

Because effectively stabilizing streams requires an understanding of ecology and fluvial processes, the guidance document includes sections on these subjects. We also addressed some broader stream restoration and management issues although these issues are too broad to completely cover in a single document. Therefore, we emphasize that this guidance is a work in progress, and we have merely scratched the surface of the subject.

Because this is a working document, we plan to place it on the Waterways Experiment Station (www.wes.army.mil/el) and Fort Worth District (www.swf.usace.army.mil, select "Permits) home pages. A bibliography is not available with the publication of the initial version of this working document, but will be posted on the home pages as soon as it is prepared.

Stream Systems

There are approximately 105,000 miles of streams in the Fort Worth District of the U.S. Army Corps of Engineers. Major river systems within the boundaries of the Fort Worth District include the Angelina, Brazos, Colorado, Neches, Rio Grande, Sabine, Sulphur, and Trinity. These rivers and the streams that feed them perform many functions that are valuable to society. The public is probably most familiar with the roles these streams play in water supply, floodflow attenuation, recreation and in improving the scenic quality of the environment. Natural resource managers recognize some of the less visible benefits as well. The streams provide habitat and migration corridors for an extremely large array of aquatic and terrestrial wildlife, they buffer pollutants, they recharge aquifers, and they cycle and convert energy and nutrients.

Stream alteration and land use change in watersheds impact the physical, chemical, and biological processes of streams. Many of these impacts are adverse to the beneficial functions of streams, so designers and approving officials must consider each stream function using a multi- discipline approach and generally follow a sequence of avoiding adverse impacts, minimizing adverse impacts, and compensating for unavoidable adverse impacts to the maximum extent practicable. An integrated approach to design and monitoring of stream modification projects will ensure protection of stream systems that are critical to the efforts of the Fort Worth District Regulatory program to protect the chemical, physical, and biological integrity of the nation's waters under Section 404 of the Clean Water Act.

Stream Dynamics

Within stream and riparian ecosystems exists a set of complex relationships between variables that dictate the physical, biological and chemical character of the environment. Streams constantly adjust in response to changes in flow, sediment yield, and boundary modifications. Erosion of stream banks, development of islands and bars, and changes in geometry are some of the ways streams adjust to ever changing conditions.   Stream management, stabilization, and restoration require a knowledge and awareness of the complex interactions between watershed and stream processes, boundary sediments, and bank and floodplain conditions. Identifying the causes of channel instability or potential instability and having knowledge of the magnitude and distribution of channel adjustment processes are necessary to:

- Estimate future channel changes
- Develop appropriate mitigation measures
- Preserve and protect the stream corridor

Anthropogenic Impacts

The dynamic processes that occur on streams are all quite natural, and erosion and sedimentation regularly occur on even the most pristine stream systems. These processes become "problems" only because society deems them so. Stream and riparian modification projects are undertaken for a variety of reasons - most commonly to preserve investments in property or infrastructure.   Streams are also altered and stabilized to maintain predictable forms and conditions so that risks to instream and riparian uses (e.g. navigation, agriculture) are minimized.

The relationships between stream erosion and social values must be recognized. Human activities such as urbanization, channelization and other land uses contribute to accelerated erosion. At the same time, infrastructure development along streams increases the likelihood of conflict between erosion and social needs to protect property. Many of the adverse consequences of development can be avoided through careful planning or mitigated through land-use adjustments. Others will require direct intervention using erosion control measures. An increasing appreciation for the environmental value of our stream systems has led to a revival of old methods and the development of new techniques that not only provide erosion control but also restore or enhance the aquatic and riparian environment.

Restoration and Management

Restoration designers are responsible for engaging in one of three general approaches to achieve dynamic equilibrium and functional objectives within a stream corridor. These three approaches are:

- Undisturbed self-recovery: where the stream ecosystem is recovering rapidly, and a forced design is unnecessary and may even be detrimental.
- Assisted recovery: where a stream ecosystem is attempting to recover, but doing so slowly or uncertainly. In such a case, design may facilitate natural processes already occurring.
- Full restoration: rebuilding functions that are beyond the repair capacity of the ecosystem or are occurring beyond a desirable time frame. This approach requires not only an understanding of the stream corridor's condition but also the full potential of design to balance the restoration of dynamic equilibrium with the needs of society.

These approaches are listed in general order of preference. The reverse tends to be the case in practice - designers rush to "reconstruct" channels rather than ascertain the minimum amount of intervention needed to achieve the objectives.

An alternative to the restoration approaches listed above, all of which are reactive, is to take a proactive role in preventing or minimizing degradation. Measures that avoid or mitigate the affects of urbanization on hydrology and sediment yield, and approaches to the preservation of riparian buffers can eliminate many of the adverse impacts that accompany development in urban areas. Such efforts are encouraged not only from a natural resource stewardship perspective, but from an economic standpoint as well. Repairing a damaged ecosystem is generally much more costly that preventing the degradation.

Soil Bioengineering

One means of addressing bank erosion is through the use of soil bioengineering. Soil bioengineering is the use of live and dead plant materials, in combination with natural and synthetic support materials, for slope stabilization, erosion reduction, and vegetative establishment. Soil bioengineering techniques can be very useful in meeting multi-objective erosion control projects. Techniques presented in this handbook can be used to concurrently control erosion, provide fish habitat, and enhance aesthetics, for example.

There are many soil bioengineering systems, and selection of the appropriate system or systems is critical to successful erosion control. Reference documents should be consulted to ensure that the principles of soil bioengineering are understood and applied. The NRCS National Engineering Handbook (Part 650, Chapter 18 Soil Bioengineering for Upland Slope Protection and Erosion Reduction and Chapter 16 Streambank and Shoreline Protection) offers background and guidelines for application of this technology. A detailed description of soil bioengineering systems is offered in the U.S. Army Corps of Engineer Waterway Experiment Station report "Bioengineering for Streambank Erosion Control" (Allen and Leach, 1997). Information from these sources and the experiences of the authors is summarized in this handbook.

Purpose and Scope

This handbook is designed to provide guidance to cities, counties, federal and state agencies, private consultants, private developers, and others. The USACE and our partners in this effort believe that this handbook will help produce projects that have less adverse effect on the aquatic environment. We hope that this guidance will alter the decision-making process of designers and officials for proposed projects that may affect these important stream systems and result in considerations for maintaining, restoring, and protecting natural stream functions being incorporated into all proposals for work in waters of the United States.

This document will not make the reader an expert in erosion control, restoration or management. It is intended to introduce considerations involved in addressing stream instabilities, and to present an overview of techniques that might be considered for erosion control projects. It is also intended to help readers develop an appreciation for the issues associated with stream systems and formulate an understanding of the processes necessary to address stream management problems. The initial focus of the handbook was erosion control and streambank restoration, and these remain the principal topical areas.

Document Outline

A number of people expected this document to be a step-by-step procedure, or "cookbook", for stream restoration and streambank stabilization. To these people, we have always said that we cannot advocate such a procedure for a simple reason that bears repeating here – stream systems are too complicated to put in a box. For every project on which a generic procedure could be applied, there would be a thousand exceptions. And were the procedure to be applied to these excepted cases, failures would almost certainly result. So this document is not a roadmap but, rather, a compilation of information, guidelines, and tools that should assist in provoking thought among individuals or groups involved with stream projects.

The most important information in this document is presented in the first few chapters. Though specific details of some restoration measures are presented in later chapters, an understanding of the fundamental ecological relations on each stream project is needed to apply these techniques properly. Table 1.1 provides a quick overview of the document and its content.

Table 1.1 Document overview

Chapter	*Subjects*	*Use*
1	Background, Introduction	Provides context for the document and overview of objectives.
2	Stream Form, Fluvial Processes, Sediment Transport, and Streambank Failure	Describes the physical processes on stream systems and their response to a variety of impacts. This information is fundamental to identifying the causes of stream degradation and the potential benefits of a variety of preventative and remedial measures.
3	Stream Functions, Ecological Characterization, and Habitat Assessment	Describes the ecology of streams and riparian systems and presents a functional basis to evaluate streams. This basic information helps users understand the chemical and biological consequences of physical changes to the stream and riparian system.
4	Data Collection and Analysis	Presents cursory information on data collection and analysis techniques for a variety of subject matter. The focus of this chapter is on identifying information that helps establish the underlying causes of stream problems.
5	Bioengineering Techniques	Presents an overview of a number of streambank restoration techniques. The various techniques are discussed in the context of their position on the bank.
6	Watershed Management and Streambank Restoration Alternatives	Techniques and information to help users select among alternatives is presented. Advantages and limitations of various techniques are discussed.
7	Design	Design procedures, techniques, criteria and guidance for a number of stream restoration, streambank stabilization and watershed management practices are given.

Monitoring and Maintenance

We had originally compiled an eighth chapter to this document that addressed construction, monitoring and maintenance. Unfortunately, time expired before we could complete the chapter, and we elected to remove it altogether. But we want to emphasize that these issues should not be overlooked. A properly designed monitoring system and associated maintenance are vital to the success of riparian ecosystem creation/restoration efforts. Equally important, and closely related, project objectives should be stated in quantifiable and measurable terms. Unfortunately, objectives of creation/restoration projects are rarely stated in quantifiable terms, and monitoring and maintenance are soon forgotten after the project is implemented. Likewise, the best plans are of little good if not properly constructed.

2 Stream Form and Fluvial Processes

Chapter Overview

Chapter 2 presents a few fundamental concepts regarding the morphology of stream channels and the processes that shape them. Water and sediments are the principal agents that shape channels, so this chapter introduces hydrology, hydraulics, and sedimentation. Of course, it is impossible to adequately address these topics in a few dozen pages, so the intent is to merely introduce the subjects and alert readers to their importance in stream restoration and management. The chapter concludes with a discussion of streambank erosion and failure, the major focus of this text.

Stream Form

The form a stream takes provides many clues to its behavior. Understanding stream form is a necessary first step in evaluating and predicting fluvial (riverine) mechanics, geomorphology, stream stability, habitat characteristics, and functional potential. These, in turn, are necessary to develop alternatives for the restoration and management of our stream systems and to make an informed choice among alternatives.

Channel Morphology

A minimal description of a channel's morphology requires that its grade, planform, cross-section geometry and some measure of the channel resistance be parametrically defined. Channel grade can be described by the thalweg slope, S_o, and resistance by the friction slope, S_f. Figure 2.1 shows various slopes that can be used to characterize channel grade and demonstrates that these slopes may not be equal. Channel planform requires at least two parameters, sinuosity and meander arc length, for example. To uniquely define the cross-sectional geometry of a channel requires that at least one variable be specified in addition to the width and depth. Maximum depth, bank slope and a channel shape factor are examples of a third variable that may be considered. Figures 2.2 and 2.3 show the parameters commonly used in describing channel geometry and planform.

For convenience, both cartesian and curvilinear coordinate systems are used in defining the planform as depicted in Figure 2.3. The principal axis in the cartesian system, x, defines the center line of the meandering pattern in the downstream direction for planform analysis, and is aligned with the stream and horizontal for cross section and grade analyses. The y and z axis alignments are with the vertical and horizontal, both normal to the flow. In the curvilinear system, the sinuous axis s follows the centerline of the stream, and the transversal direction remains orthogonal to the principal axis in the horizontal.

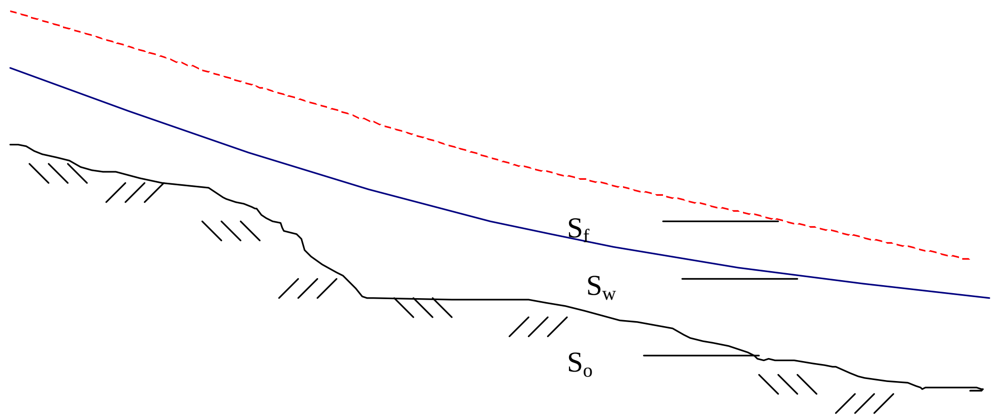


Figure 2.1 Different slopes used to characterize channel grade.

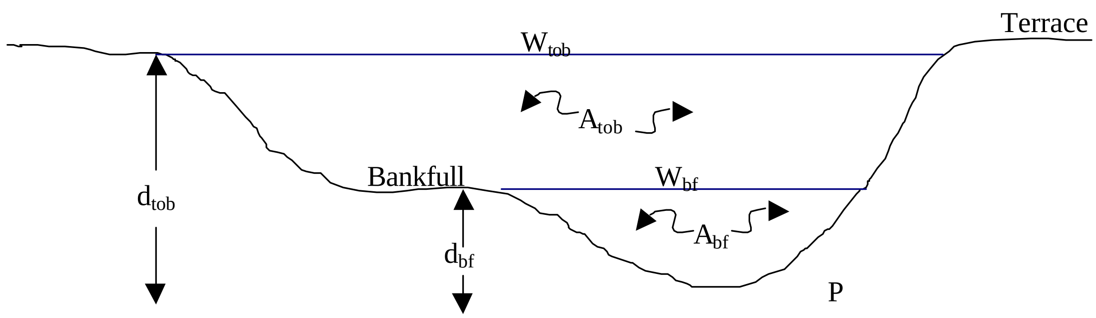


Figure 2.2 Channel cross section definition.

Planform and Grade

Natural channels occur in three general forms: straight, braided, and meandering (See Figure 2.4 and Table 2.1 on following pages for further clarification). The distinction between straight and meandering rivers is made on the basis of sinuosity. Sinuosity is the length between two points on a stream, following the channel, divided by the straight-line distance between the two points. For example, a stream segment of 1500 ft along the channel thalweg but only 1000 ft long in a straight-line between the beginning and ending points would have a sinuosity of 1.5 (1500 ÷ 1000). Another measure of sinuosity is the valley slope divided by the channel slope.

Straight channels have a sinuosity less than 1.4. Braided rivers are characterized by wide shallow flows, steep slopes, and high sediment loads. Meandering channels are characterized by alternate pool-riffle sequences and a planform with a sinuosity exceeding 1.4. Many investigators have developed classification systems to further define a river's form.

Channel grade or slope is measured as the difference in elevation between two points in the stream divided by the stream length between the two points. Three measures of slope are commonly used to characterize slope: bed slope (S_o), water surface slope (S_w), and energy or friction slope (S_f) (See Figure 2.1). Slope is one of the most critical pieces of design information required when channel modifications are considered. Channel slope directly impacts flow velocity and shear stress. Because these attributes drive the geomorphic processes of erosion, sediment transport, and sediment deposition, channel slope becomes a controlling factor in channel shape and pattern. The slope of a stream is seldom uniform, even over short reaches. Differences in geologic material, vegetation patterns, or human disturbances can result in significant local slope variations.

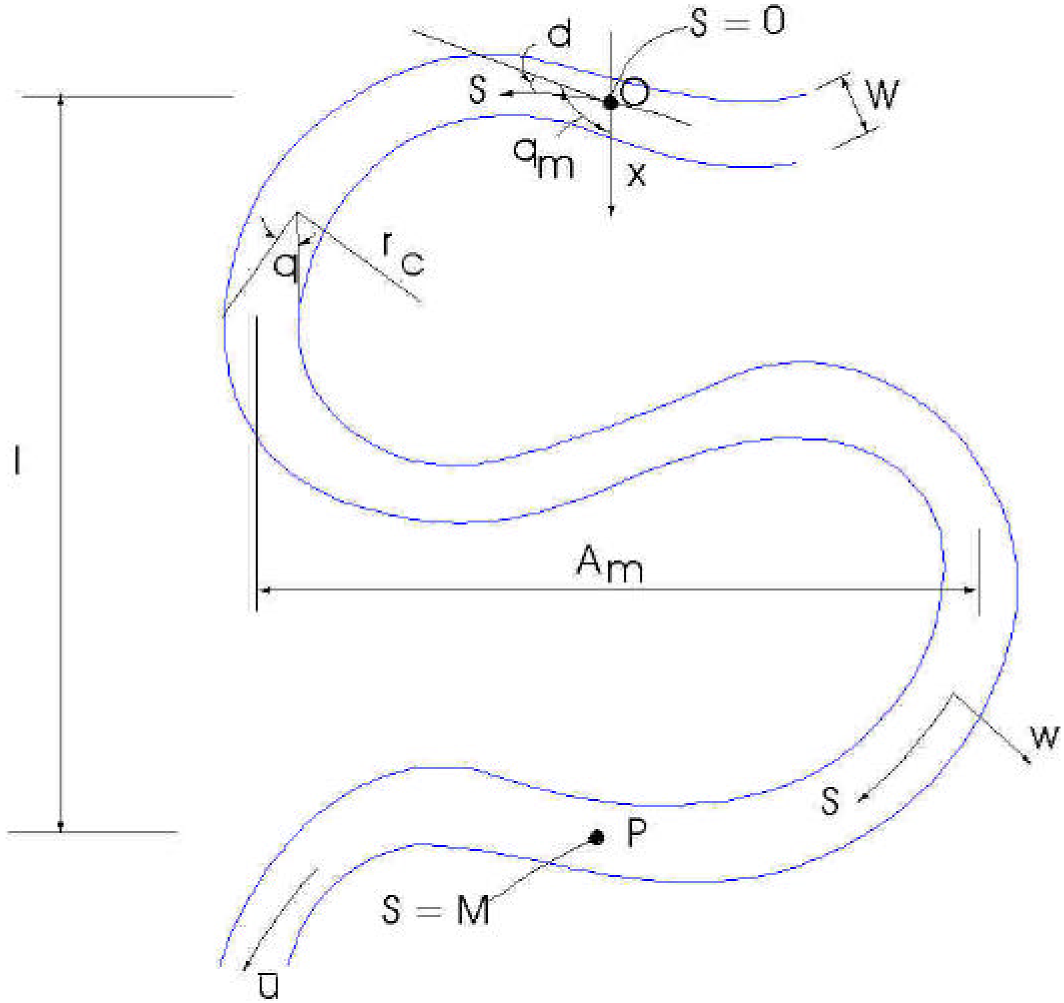


Figure 2.3 Channel planform definition.

Table 2.1 Descriptions of various channel planform characteristics.

Distinction/Type	*Description*
Pattern	
Straight	Very little curvature occurs mainly in braided channels, delta distributaries, and structurally controlled rivers.
Sinuous	Slight curvature with a belt width of less than approximately two channel widths
Irregular	No repeatable pattern. Many braided and split channels fall into this category.
Irregular Meanders	A repeated pattern vaguely present in channel plan; free meanders of sand-bed channels with high bed load, and many entrenched meanders are irregular.
Regular Meanders	Characterized by a clearly repeated pattern. The angle between the channel and the valley axis is less than 90°.
Tortuous Meanders	A more or less repeated pattern with angles greater than 90° between the channel axis and the valley trend.
Islands	
Occasional	Relatively stable, frequently vegetated, fewer than two islands per wavelength
Frequent	Relatively stable, vegeted, two or more islands per wavelength.
Split	Somewhat unstable, numerous, occasional overlap of two islands in a section.
Braided	Unstable, frequently overtopped, unvegetated, multiple islands in a section.
Bars	
Side Bars	In entrenched straight or sinuous channel, side bars may be developed. In very straight channels they can migrate. More frequently their position is associated with slight channel bends and therefore stable.
Point Bars	These features form on the inside of well-developed bends.
Mid-Channel Bars	The bar position remains stable over decades with bed load transport taking place across the bar. Deposition of suspended load in the lee sometimes converts them into islands.
Diagonal Bars	This bar type occurs only in gravel bed channels.
Dune Macroforms	Dune-like bar with a profile length on the order of the channel width, and height more than 50 percent of mean bankfull depth. Common in relatively active sand-bed channels.

Channel Regime

Regime is generally accepted to mean the geometric condition of a river reach that is in a state of quasi-equilibrium. Although such a reach may experience temporal and spatial variation in form and discharge of sediment or water, the variations fluctuate about a balanced mean. For most mobile-bed streams, there is a range of discharges within which the stream can adjust by varying its bed form, flow depth, and velocity without appreciably changing its slope, channel width, or planform.   Other times, streams adjust their geometry to flow events of different magnitudes by mobilizing bed or bank sediments.

Although channel shape is affected by a range of flows, it has been proposed that a single discharge, if held steady, would produce the same gross channel shapes and dimensions as the natural sequence of discharge events. This discharge is known as the channel-forming or "dominant" discharge. Researchers have used various deterministic flows to represent the channel-forming discharge.   The most common are 1) bankfull discharge, 2) a specific discharge recurrence interval from the annual peak or partial duration frequency curves, and 3) effective discharge. These three flows are roughly equivalent for stable channels, but may vary dramatically for unstable sections.

The bankfull discharge is the discharge that fills a stable alluvial channel up to the elevation of the active floodplain. In many natural channels, this is the discharge which just fills the cross section without overtopping the banks, hence the term “bankfull". Active floodplain levels are often difficult to ascertain, however, leading to many inconsistencies in the determination of the bankfull flow.

To avoid difficulties associated with field determination of bankfull stage, the channel-forming discharge is often assumed to be a specific recurrence interval discharge. Most investigations have concluded that the dominant discharge recurrence intervals range from 1.1 to 2.0 years with an average of 1.5 years. There are many instances where the bankfull discharge does not fall within this range, particularly for highly impacted watersheds.

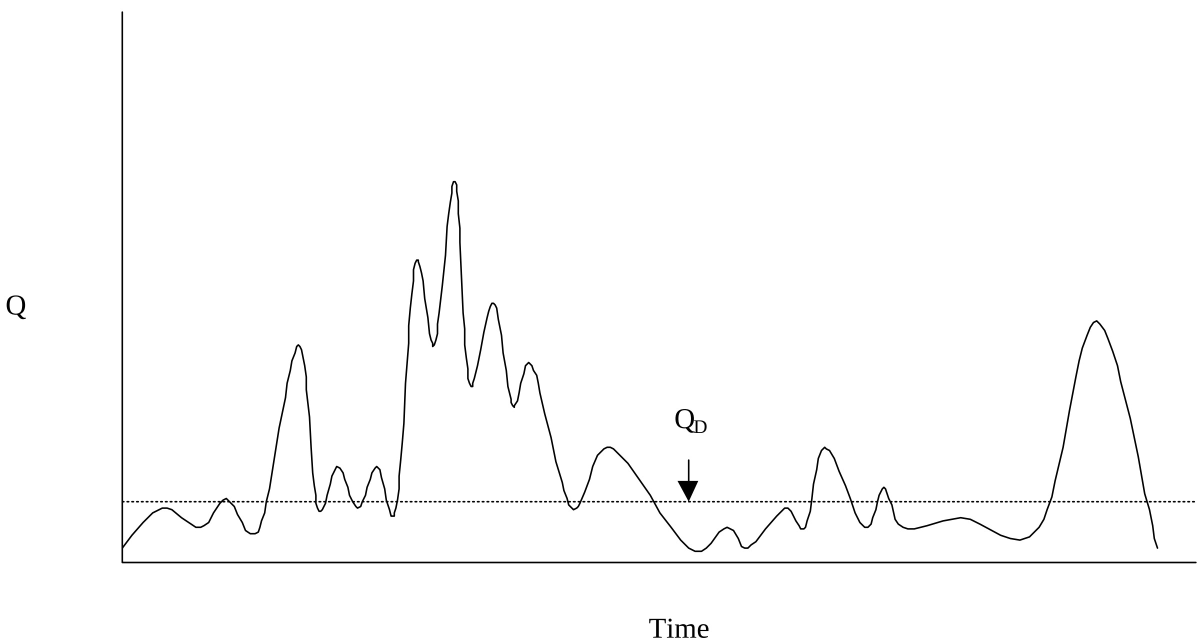


Figure 2.4 Dominant discharge, Q_D, is a single value assumed to represent varying flows.

Effective discharge is the modal (peak) value of a curve generated by integrating a bed material sediment rating curve with a flow duration curve for the stream reach in question. In other words, it is the discharge that moves the most sediment in a stream. Of the three dominant discharge determinants, effective discharge is the only one that can be directly computed in a consistent fashion. The effective discharge has morphological significance since it is the discharge that transports the bulk of the sediment. Computation of this value requires sediment data that is not always available, however.

The notion that streams can be represented by a single discharge is appealing because it simplifies the analytical challenges facing the designers of stabilization and restoration projects on streams. Unfortunately, a single discharge is seldom sufficient to evaluate the functional characteristics and performance of streams and the habitat and stabilization features we design. The dominant discharge is a logical starting point for such evaluations, but consideration must also be given to other flow events that could affect the performance of the system. For example, designers of habitat improvement projects might need to consider a low flow condition (say the seven-day-ten year low flow discharge) to select and site habitat features, an extreme flow condition (typically about the dominant discharge) to design the features for structural stability, and a design flood (generally a 100-year event) to assess impacts on water surface elevations.

Hydraulic Geometry

The cross sectional geometry of a stream is important for characterizing energy and habitat conditions. The cross section varies in meandering channels as shown in Figure 2.5. The hydraulic geometry relates cross sectional geometry to water and sediment discharge velocity, slope, planform and bed sediments. Hydraulic geometry relations are generally applicable to the riffle sections shown in Figure 2.5, not the pool sections.

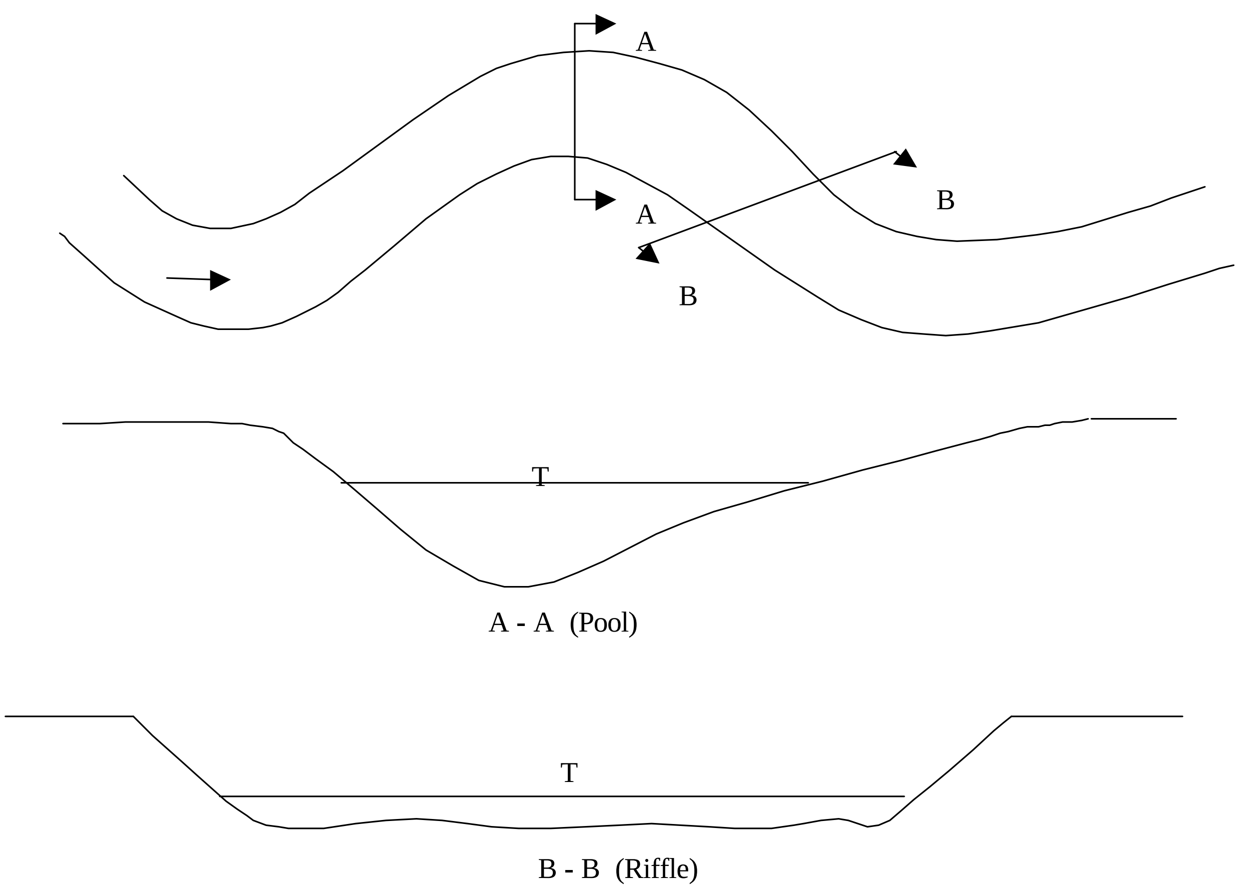


Figure 2.5. Cross section variation in a meandering stream.

Existing techniques for predicting the hydraulic geometry of alluvial channels can be placed into two categories: (1) empirical regime equations derived from regression analyses of observed channel geometries; and (2) analytical models that attempt to model rivers on a rational basis using theoretical considerations. Hydraulic geometry relations can be further distinguished as at-a-station or downstream.

Regime equations generally relate some two-variable combination of velocity, width, depth, slope, area, hydraulic radius, perimeter or discharge as a power function. The regime concepts provide some insight into the relationships between pertinent variables but, by and large, they remain empirical and thus are limited in application to the range of conditions for which they were developed. The at-a-station relations can be generalized in the form of the following equations where, by continuity, a*c*k = 1 and b+e+m=1:

$$W = aQ^b$$

$$D = cQ^e$$

$$V = kQ^m$$

Wargadalam (1993) showed that the existing body of literature on downstream hydraulic geometry relations can be reduced to no fewer than 176 equations describing depth, width, velocity and slope in the form:

$$D, W, V, \text{or } S_0 = a_1 Q^{b_1} d_s^{\,c_1} Q_s^{\,e_1}$$

Regime relations can be very useful tools in evaluating stream systems. They can also be very misleading if applied improperly. Common mistakes in the use of regime relations include (1) application beyond the data upon which the relation is based and (2) the use of the wrong measure of for a parameter in the equations. The list below includes a few example relations chosen from a project recently completed by the authors. In these relations, the variables have different values among the equations and include the following variations: Q = discharge (bankfull, 2-year annual peak, 2-year partial duration),
W = channel width (bankfull, top of bank, water surface), d = mean depth (to water surface, to bankfull), V = mean velocity.

Bray (1982)	W=2.38*Q2^.53
(General)	d=0.226*Q2^.33
	V=1.58*Q2^.14
Emmett (1972)	W=2.39*Qbf^.5
(Alaskan Meander Streams)	d=.26*Qbf^.35
	V=1.62*Qbf^.15
Drage & Carlson (1977)	W=4.66*Qbf^.47
(Braided Streams)	d=.13*Qbf^.38
	V=1.65*Qbf^.15

General Hydraulic Model Beschta (1992)	$W=aQ2^{.5}$ $d=cQ2^{.4}$	(a and c vary with channel shape)
USGS Channel Width Williams (1986)	W=(Q2/.4)^1/1.82 D=0.12W^0.69	
Lacey (1948)	W=2.67Qbf^.5 D=(Qbf/(13.5*((D_{50}*25.4)^0.5)))^0.333	
Yukon Placer 1990 DFO	W=2.73*Qbf^0.5 D=0.22*Qbf^0.333	
Chang (1988)	W=[1.905+0.249(ln(0.0001065*D_{50}^1.15)/(S*Qbf^0.42))]*Qbf^0.47 D=[0.2077-0.0418(ln(0.000442*D_{50}^1.15)/(S*Qbf^0.42))]*Qbf^0.42	

The above equations were applied to a cobble-bed stream in southwest Alaska, and several of the relations are not appropriate for use on other stream types or in other parts of the country. Another common mistake users of regime relations make is not appreciating the range of potential solutions. Williams (1986), developed regime relations for the mean value and plus and minus one standard deviation for a number of channel morphology parameters. When applied to a recent project in Vermont by the lead author, the range of values can be seen to be quite large (Table 2.2).

Bed and Bank Characteristics

The origin and composition of the materials comprising a stream's bed and banks have a significant influence upon channel morphology and bank erosion. Beds and banks can be classified as cohesive, non-cohesive, or composite. From a practical standpoint, cohesive beds and banks can be described as those containing appreciable amounts of clay. A better technical description might be that a cohesive sediment mixture is one in which the internal shear strength is increased over that expected from the simple discrete particle properties of shape, size, density, and relative position. The increase is usually due to molecular attraction (as the case with most clays), but could also be caused by such things as the binding strength generated by plant root masses.

Non-cohesive materials, as the name implies, do not possess this added strength. Sands and gravels are non-cohesive sediments, as typically are silts. Composite banks, which have a layered structure containing both cohesive and non-cohesive materials, are commonly found on rivers with a high bed load. Lower portions of the bank are historic bar deposits of non-cohesive bed material, while the cohesive upper banks were formed by fine sediment deposition during flood recession.

Table 2.2 Variation in computed variables from regime relations

Computed Channel Variables							
Meander Wave Length				Channel Bend Length			
	S/D -	MEAN	S/D +		S/D -	MEAN	S/D +
Lm=	760	1000	1320	M=	608	800	1056
Lm=	817.608	1075.8	1409.298	M=	647.064	851.4	1115.334
Lm=	864.777	1041.9	1260.699	M=	641.654	867.1	1170.585
Belt Width				Radius of Curvature			
	S/D -	MEAN	S/D +		S/D -	MEAN	S/D +
Am=	463.6	610	799.1	RC=	182.6	220	266.2
Am=	474.24	624	817.44	RC=	153.92	208	280.8
Am=	470.304	662.4	940.608	RC=	133.98	231	328.02
Bankfull Xsection Area				Bankfull Width			
	S/D -	MEAN	S/D +		S/D -	MEAN	S/D +
A=	95.31606	194.5226	394.8808	W=	34.98659	79.51497	124.0434
A=	98.7179	235.0426	564.1023	W=	38.80883	88.2019	137.595
A=	126.0822	247.2199	487.0232	W=	32.28194	87.24848	142.215
A=	115.5494	275.1176	654.7799	W=	46.68738	89.78342	132.8795
Bankfull Mean Depth				Area			
	S/D -	MEAN	S/D +		S/D -	MEAN	S/D +
D=	1.443949	2.57848	4.615479	Lm=	719.1976	1141.584	1815.118
D=	1.720956	2.967166	5.103526	M=	477.1819	837.1613	1481.775
D=	1.61158	2.685967	4.458706	Am=	438.3681	684.9501	1068.522
D=	1.630929	3.077225	5.846728	RC=	220.7062	220.7062	388.4428
Width				Depth			
	S/D -	MEAN	S/D +		S/D -	MEAN	S/D +
Lm=	619.2299	1015.131	1674.966	Lm=	604.1382	1473.508	3565.889
M=	421.0763	690.289	1138.977	M=	432.2289	982.3385	2239.732
Am=	279.364	582.0084	1012.695	Am=	427.0717	908.6631	1953.626
RC=	131.967	203.0262	314.6906	RC=	149.561	257.8639	683.3392

Fluvial Processes

Flow Characterization

Open channel flow can be classified based on four criteria (Table 2.3). The type of analysis and the tools used for analysis of flow depend on the flow class. Simple mathematical models can be used if the flow is assumed to be uniform and steady but flow in natural rivers is characteristically non-uniform and unsteady. Practitioners of river engineering must understand the underlying assumptions and limitations of equations used to assess river conditions.

Table 2.3 Types of flow in open channels.

Type of flow	***Criterion***
Uniform/Non-uniform (varied)	Velocity is constant/variable with space
Steady/Unsteady	Velocity is constant/variable with time
Laminar/Turbulent	Reynolds' Number, R_e, is < 500/ > 2500, (when 500< R_e <2500, flow is transitional)
Subcritical/Supercritical	Froude Number, F_r, is < 1/> 1, (when F_r= 1, flow is critical)

Where

$$R_e = R_h V/n$$

And

$$F_r = V/\sqrt{gh}$$

V – Cross section average velocity;
R_h - hydraulic radius;
h - depth of flow;
ν- kinematic viscosity;
g - gravity constant

Streamflow at a cross section is computed using the simplified form of the continuity equation:

$$Q = AV$$

where:
Q = channel discharge
A = channel cross sectional area
V = average channel velocity

The energy equation is used to calculate changes in water-surface elevation between two relatively similar cross sections in a stream. A simplified expression for this equation is:

$$z_1 + d_1 + V_1^2/2g = z_2 + d_2 + V_2^2/2g + h_e$$

where:
z = minimum elevation of stream bed
d = maximum depth of flow
v = average velocity

g = acceleration of gravity
h_e = energy loss between the two sections

Subscript 1 indicates that the variable is at the upstream cross-section, and subscript 2 indicates that the variable is at the downstream cross-section. The energy grade line is a theoretical line whose elevation above the streambed is the sum of the water surface elevation and a term that represents the kinetic energy of the flow ($V^2/2g$). The slope of the energy grade line represents the rate at which energy is dissipated through turbulence and boundary friction. This simplified equation is applicable when hydraulic conditions between the two cross-sections are relatively similar (gradually varied flow), and the channel slope is small (less than 10 degrees).

Velocity

Velocity is a vector quantity having both magnitude and direction. It varies in four dimensions:

(i) With distance from the stream bed - The shape of the vertical velocity profile is strongly influenced by the size of roughness elements on the stream bed and the depth of flow (h). If the former is expressed in terms of bed material size (d), the two variables can be incorporated in a single index, the relative roughness ratio d/h. Stream beds generally contain a range of grain sizes, so the problem is to select a grain diameter which best expresses this component of resistance.

(ii) Across the stream - Velocity increases toward the center of a stream as the frictional effects of the channel banks decline, but the degree of symmetry in cross-channel velocity can be highly variable, changing with the shape and alignment of the channel. In particular the velocity distribution in channel bends is characteristically asymmetric, with the main current moving toward the outer bank. In shallow channels, the velocity gradient is steepest (and therefore the boundary shear stress greatest) against the bed. In narrow, deep sections the velocity gradient is steepest against the banks, producing a greater tendency for bank erosion.

(iii) Downstream- In addition to local fluctuations, change in velocity at the longitudinal scale has been a major interest of geomorphologists concerned in particular with the development of an equilibrium stream profile. Despite a declining slope along most rivers, velocity tends to remain constant or increase slightly as the channel becomes hydraulically more efficient and resistance decreases in the downstream direction. Variations in the rate of change of velocity do occur both along and between rivers, since velocity is merely one variable that can be adjusted to accommodate the downstream increase in discharge.

(iv) With time- Over time-periods measured in seconds, point velocities may reach values of 60-70 percent or more of the time average velocity because of the inherent variability of turbulent flow, thus making it difficult to define the initiation of particle motion in terms of velocity. At the larger time scale of days, weeks or months, velocity responds to fluctuations in discharge. The increase in depth with discharge tends to mask roughness elements in the bed and thereby produce an increase in velocity. However, the effect is not uniform and the exponent m (the rate of change of velocity) in $v = kQ^m$ can vary considerably from section to section.

Velocity is thus a highly variable quantity in time and space. The character of that variation is important since velocity influences the processes of erosion, transportation and deposition. Velocity is usually measured by a current meter at selected points in the flow cross-section and expressed as an average value. However, mean velocity at a cross-section is not the most relevant measure for defining the initiation of erosion. It remains the most widely used parameter, partly because of measurement difficulties associated with other parameters.

Resistance

Energy losses between the two cross sections occur due to channel boundary and geometric form resistance. Factors contributing to flow resistance include:

a) surface roughness,
b) vegetation,
c) channel irregularity,
d) channel alignment,
e) silting and scouring,
f) obstructions,
g) size and shape of the channel,
h) stage and discharge,
i) seasonal changes, and
j) suspended material and bed load.

These resistances can be combined into a roughness coefficient for use in equations to evaluate energy losses in a channel. In the US, it is customary to express the flow resistance in terms of the resistance coefficient, n, from Manning's Monomial Equation. Manning’s equation for mean velocity, V (in feet per second or meter per second), is given as:

$$V = \frac{k_n}{n} R^{2/3} S^{1/2}$$

where:
n = Manning’s roughness coefficient,
R = hydraulic radius (Area/wetted perimeter),
k_n = 1 (SI units),
k_n = 1.486 (ft-lb-sec units), and
S = energy, momentum, or water surface slope (depending on conditions).

Manning’s equation was developed for conditions of uniform flow in which the water surface profile and energy gradient are parallel to the streambed, and the area, hydraulic radius, and depth remain constant throughout the reach. The Manning equation is also used to calculate friction losses in natural channels with gradually varied flow. In this case, calculations proceed from one cross section to the next, and unique hydraulic parameters are calculated at each cross section. Computer models, such as HEC-2, perform these calculations and are widely used analytical tools.

Procedures for the computation or estimation of Manning's n can be grouped into three general categories: direct measurement, analytical approaches, and handbook methods. Direct measurement, though important for model and prototype (i.e. from high water marks) calibration and verification, is of little practical use for prediction and is not discussed.

Analytical Approaches: Cowan (1956) proposed a procedure for estimating Manning's n that takes into account the contributions of various factors, including vegetation, to total flow resistance. The procedure, popularized by Chow (1959), Aldredge and Garrett (1973), and Arcement and Schneider (1989), is based upon the concept of linearity. As such, it assumes that the resistances induced by various contributing factors can be summed to establish total resistance. Cowan extended this theory to include resistance coefficients, namely Manning's n. Cowan's equation is:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m$$

where
m = Ratio for meandering,
n_b = Base n value,
n_1 = addition for surface irregularities,
n_2 = addition for variation in channel cross section,
n_3 = addition for obstructions, and
n_4 = addition for vegetation.

Using Cowan's approach, an engineer selects a base value for n, then increases this value by adding adjustments for each of the factors described above. A coefficient for meandering is applied to the additive factors, and the resultant Manning's n value is used to calculate hydraulic parameters for the channel using whatever procedure the engineer chooses. Roughness values for channels and floodplains are determined separately since the composition, physical shape, and vegetation of a floodplain can be quite different from those of a channel. Compositing techniques are used to develop a composite roughness value for the channel/floodplain combination or the conveyance for each can be calculated and summed. Tables 2.4 through 2.6 provide the recommended adjustment factors for vegetation. The selection of an appropriate adjustment value from the tables is very subjective.

Handbook Methods: Establishment of flow resistance with procedures that do not rely on direct measurement or numerical analysis are referred to herein as the "handbook method". Included in this category are the familiar tables of roughness values and the estimation of roughness values based upon visual comparison. The handbook methods are the most widely used approaches for the evaluation of channel roughness.

Chow (1959) is regarded as the pioneer of this approach to solving for flow resistance. The tables of Manning's n values published in his book are likely the most common sources of information for the selection of a channel and floodplain roughness values. Chow provides minimum, normal, and maximum values of Manning's n for conduits, lined canals, and natural channels. Of the 111 channel and floodplain types listed in Chow's table, only 27 include vegetation, and only 11 of the 24 photographs show evidence of vegetation.

Table 2.4 Values for Calculating Manning's n by Cowan's (1956) Method

Channel conditions	Value
Material involved	***n_0***
Earth	0.020
Rock cut	0.025
Fine gravel	0.024
Coarse gravel	0.028
Degree of irregularity	***n_1***
Smooth	0.000
Minor	0.005
Moderate	0.010
Severe	0.020
Channel cross section variation	***n_2***
Gradual	0.000
Alternating occasionally	0.005
Alternating frequently	0.010-0.015
Relative effect of obstructions	***n_3***
Negligible	0.000
Minor	0.010-0.015
Appreciable	0.020--0.030
Severe	0.040-0.060
Vegetation	***n_4***
Low	0.005-0.010
Medium	0.010-0.025
High	0.025-0.050
Very high	0.050-0.100
Degree of meandering	***m***
Minor	1.000
Appreciable	1.150
Severe	1.300

The visual comparison approach relies on the use of "calibrated photographs" and associated roughness of certain channels that can be found in several references as a means of estimating roughness values for the channel of interest. Aldridge and Garrett (1973) present photographs of selected Arizona channels and floodplains having known roughness coefficients. Barnes (1967) presents color photographs and descriptive data for 50 stream channels, nearly all of which have vegetation on the banks. Unfortunately, nearly all of the data presented in Barnes' report pertains to the main channel only. Hicks and Mason (1991) is the most comprehensive reference for the visual comparison method. Color photographs and descriptions of 78 river reaches in New Zealand are provided along with roughness values calculated from field measurements, bed material gradations, discharge, water surface slope, friction slope, area, expansion expressed in percent, hydraulic radius, mean velocity, computed values for both Manning's n and Chezy's C, and an estimate of error for the computations. Most significantly, multiple discharges were evaluated for each reach. Arcement and Schneider (1989) presented photographs for 15 densely vegetated floodplains for which roughness coefficients have been verified.

Table 2.5 Adjustment values for factors that affect the channel roughness.

(Modified from Aldridge and Garrett 1973)

Amount of vegetation (n_4)	*n* value adjustment	Example
Small	0.002-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation
Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season, growing along the banks, and no significant vegetation is evident along the channel bottoms where the hydraulic radius exceeds 2 ft
Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 ft; bushy willows about 1 year old intergrown with some weeds along side slopes (all vegetation in full foliage), and no significant vegetation exists along channel bottoms where the hydraulic radius is greater than 2 ft
Very Large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foliage), or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full foliage)

Table 2.6 Adjustment values for factors that affect the floodplain roughness.

(Modified form Aldridge and Garret 1973, Table 2)

Amount of vegetation (n_4)	*n* value adjustment	Example
Small	0.001-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation
Medium	0.011-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season
Large	0.025-0.050	Turf grass growing where the average depth equals the height of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 ft; mature row crops, or mature field crops where depth of flow is at least twice the height of the vegetation
Very large	0.050-0.100	Turf grass growing where the average flow depth is less than half the vegetation height; moderate to dense brush, or heavy stand of timber with few down trees and little undergrowth where depth of flow is below branches; mature field crops where depth of flow is less than the height of the vegetation
Extreme	0.100-0.200	Dense bushy willow, mesquite, and saltcedar (all vegetation in full foliage): heavy stand of timber, few down trees, depth of flow reaching branches

Although many practicioners believe that roughness coefficients, such as Manning's n, are constant for a channel reach, this is simply not the case. Both spatial and temporal variability of Manning's n values have been well documented. The variability is particularly pronounced in vegetated channels, as shown by Table 5.

Table 2.7 Stochastic Characteristics of n For Vegetated Channels

Source	*Description*	*No. Obs.*	*Min*	*Mean*	*Max*	*CV*
Bakry et al. (1992)	28 Canals w/ Bank Veg. (space-time)	280	0.011	0.032	0.083	0.40
Bakry et al. (1992)	9 Canals w/ Aquatic Veg. (space-time)	156	0.020	0.051	0.183	0.40
Powell (1978)	River Bain Aq. Veg. (periodic '67-'71)	260	0.020	n/a	0.690	n/a
Powell (1978)	River Bain Aq. Veg. (15-min intervals '71-'77)	Approx. 120000	0.020	n/a	4.480	n/a
Watts and Watts (1990)	River Yare Aq. Veg. (seasonal variability)	9	0.015	0.094	0.160	0.56
Watson (1987)	9 Sites, River Ebble (space-time)	approx. 20	0.009	n/a	0.412	n/a
Wilson (1973)	Hanging Moss Crk., MS (space-time)	14	0.020	0.045	0.074	0.39

At the present stage of knowledge, selection of an n value requires an estimate of the resistance to flow in a given channel, which is a matter of intangibles. To veteran engineers, this means the exercise of sound engineering judgment and experience; for beginners, it can be no more than a guess, and different individuals will obtain different results. The presence of vegetation in the channel, on the banks, or in the floodplain can significantly complicate the prediction of channel stability and hydraulic characteristics. Fischenich (1995) and Yen (1992) are among authors who have recently summarized the state of the art in the prediction of resistance values in alluvial channels. Both concluded that additional work is required, particularly in the case of channels with appreciable vegetation.

Qualitative Response of Stream Systems

An alluvial river is generally and continually changing its shape, position, and characteristics as a consequence of the forces imposed upon it. The magnitude of these changes depend upon the time reference over a geologic time scale. Significant changes may occur that are of little reference to bank protection or restoration plans. Generally speaking, we are concerned with changes that occur over human time scales.

A "stable" alluvial stream is said to be in dynamic equilibrium when, over the long term, sedimentation processes are balanced such that the channel maintains its general morphology. A stream's morphology is a consequence of its response to the two principal driving, or independent variables - runoff and sediment yield - acting in concert with the channel boundary conditions to determine the channel planform, cross section, and grade. Boundary conditions include the valley slope, geology, resistance, soil type and size, and vegetation character (Figure 2.6). They also include natural or manmade controls such as dams, bridges, and water levels of receiving water bodies.

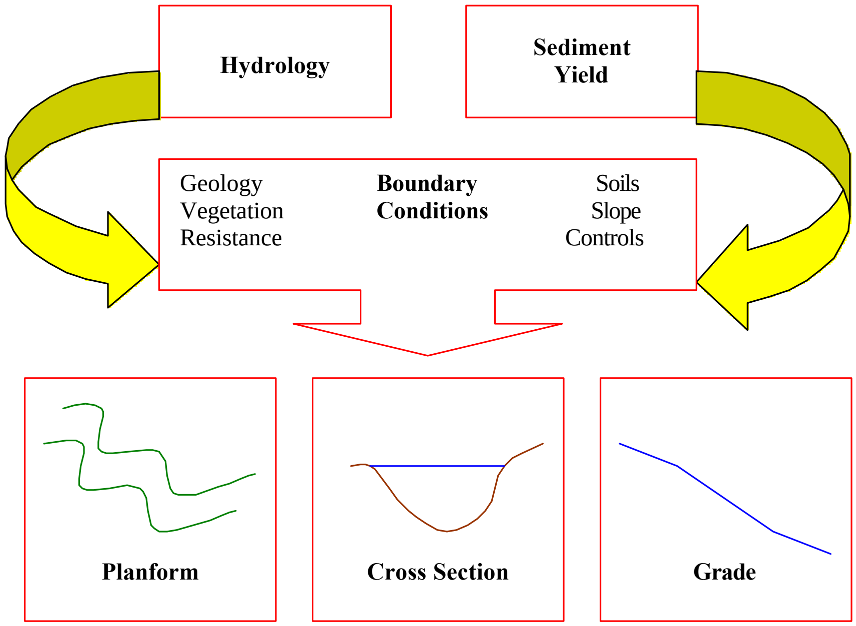


Figure 2.7 Variables affecting channel form.

Changes in sediment load, flow regime, and boundary conditions can disrupt the balance, resulting in a stream that undergoes rapid morphologic changes. When long term erosion exceeds sedimentation, channel incision occurs. Channel modification and urbanization are probably the most common causes. Other causes of channel incision include reduced sediment load due to upstream dams and increased peak flows caused by.

In a typical incising channel, the streambed degrades until critical bank height is exceeded and the bank fails, increasing channel width and sediment load. In severe cases, nick points and nick zones migrate upstream and destabilize a large part of the system upstream from the initial disturbance. Over time, the stream will move toward a new equilibrium and incision will cease when one or a combination of the following conditions develops:

- Incision upstream, sedimentation downstream, and bank failure flattens the longitudinal slope and widens the channel until flow velocity and bed shear stress drop below erosive levels.
- Fine sediments are eroded away leaving only coarse sediments that armor the streambed sufficiently to preventing further incision.
- The thalweg encounters hard substrate slowing or stopping incision.
- Recovery of riparian and instream vegetation increases streambed and stream-banks cohesion.

A new equilibrium may take decades or even centuries to achieve. Schumm et al. (1986) present a model for channel evolution in Mississippi streams that describes the stages of channel response as presented above, and demonstrated that the temporal process discussed above can also be viewed as a spatial process (Figure 2.7). Degradation of receiving channels can initiate headcuts that upstream, leading to rapid channel incision even in the absence of watershed impacts.

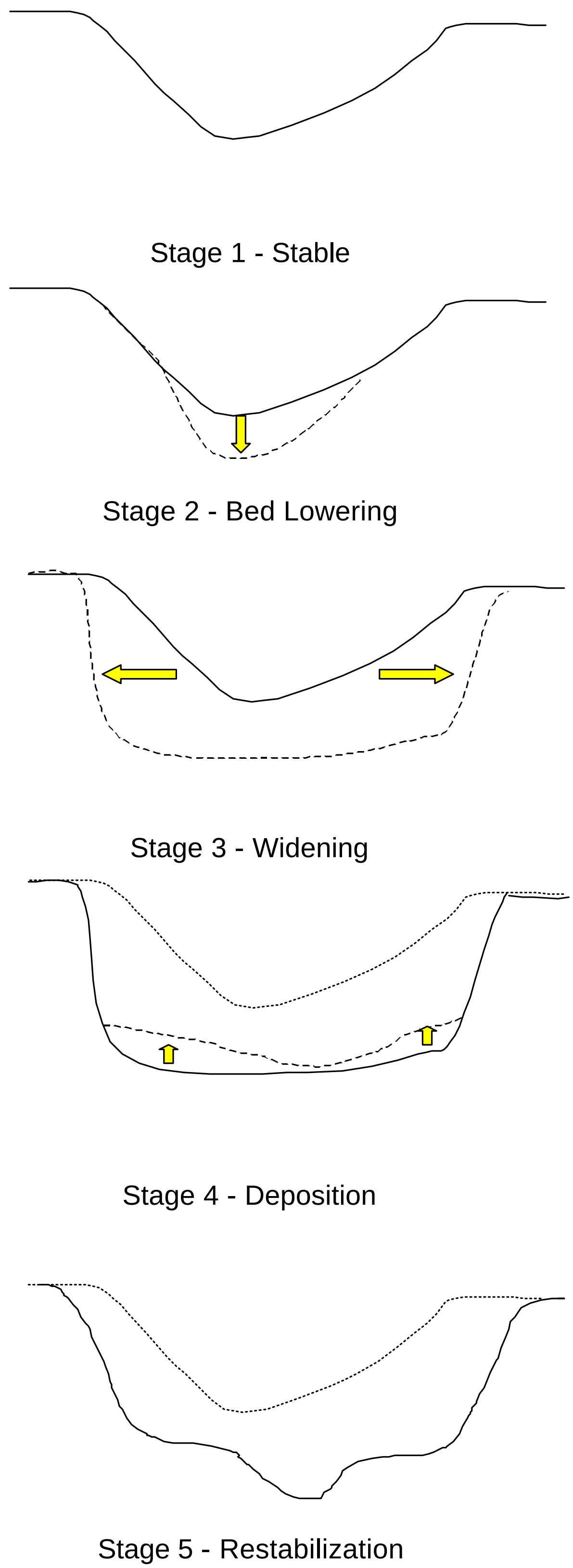


Figure 2.7 Stages of channel incision.

A typical incised channel is deep, broad, and lacks a defined or stable low-flow channel. The banks are steep and subject to ongoing failure. Pool habitat is usually lacking and riparian vegetation is often rare or absent. Much of the original floodplain habitat may have been destroyed by erosion or left permanently dry by the receding streambed. Incising channels has been a major cause of destruction and deterioration of floodplain habitats and associated wetlands.

The fluvial processes involved in channel response to urbanization are extremely complicated and the variables of importance are often difficult to isolate, unlike rigid boundary hydraulic problems. The major factors affecting alluvial stream channel forms are: (1) stream discharge, (2) sediment load, (3) longitudinal slope, (4) bank and bed resistance to flow, (5) vegetation, (6) geology, (7) sediment composition, and (8) works of man. This section discusses some of these factors and their interrelated variables.

Differentiating between local and systemwide channel-stability problems in a disturbed stream or constructed channel is necessary, and caution must be exercised if only local treatments on one site are implemented. During basinwide adjustments, stage of channel evolution will usually vary systematically with distance upstream. Downstream sites might be characterized by aggradation and the waning stages of widening, whereas upstream sites might be characterized (in progressive upstream order) by widening and mild degradation, then degradation, and if the investigation is extended far enough upstream, the stable, predisturbed condition. This sequence of stages can be used to reveal systemwide instabilities.

One of the earliest relationships proposed for explaining stream behavior was suggested by Lane (1955), who related mean annual streamflow (Q_w) and channel slope (S_o) to bed-material sediment load (Q_s) and median particle size on the streambed (D_{50}):

$$Q_w \, S_0 \propto Q_s \, D_{50}$$

Lane suggested that a channel will maintain dynamic equilibrium by balancing changes in sediment load and bed-material size with changes in streamflow or channel gradient. This general relation is demonstrated graphically in Figure 2.8.

In urban systems, the reduction to infiltration (from paved surfaces, homes, etc.,) results in increased runoff (i.e. Q_w increases). When Lane's relation is applied to this condition, one or more of the other parameters in the relation must respond to offset the change. A decrease in slope, or an increase in sediment discharge or size is needed. In fact, all three of these parameters respond to the increase in discharge. The channel incision process described above reduces the channel slope, sediments eroded from the bed and banks increase the sediment discharge, and sorting processes in the bed form an armor layer, increasing the sediment size.

The process described above is just the initial response, and as the bed slope continues to decrease, this in turn must be offset by the other parameters. In time, the sediment discharge decreases, largely offsetting the decreased slope, but the other two factors respond as well. Lane's relation, while useful for estimating qualitative system response, is of little practical value in quantifying these impacts. More rigorous techniques based upon an understanding of sediment transport phenomena are required.

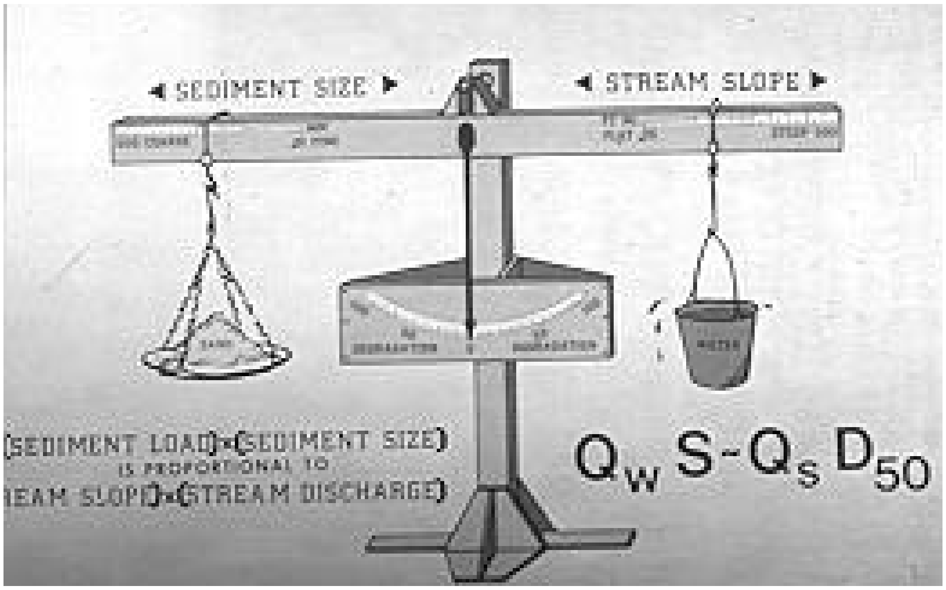


Figure 2.8 Graphical depiction of Lanes Relation

Stability and Sediment Transport

The sediment particles found in the stream channel and floodplain can be categorized according to size. Regardless of the size, all particles in the channel are subject to being transported downslope or downstream. The movement of particles depends on their physical properties, notably size, shape and density. Exactly when movement occurs for any particular particle, however, depends on the stream's hydraulic conditions and the position of the particle in the stream.

The best description of the stream's hydraulic condition (in terms of sediment transport) is the shear stress, which varies as a function of flow depth and slope. Assuming constant density, shape, and grain roughness, the larger the particle, the greater amount of shear stress needed to dislodge it and move it downstream.

Table 2.8 Grain-size classification.

Class name	Size range (mm)	Size range (in)
Boulders	≥ 256	≥10
Cobbles	64-256	2.5-10
Gravel	2-64	0.08-2.5
Sand	0.064-2	0.003-0.08
Silt	0.004-0.0064	0.001-0.003
Clay	≤0.004	<0.001

Shear Stress Distribution

Water is a viscous fluid that cannot resist stress, however small. The viscous shear stress (τ) is:

$\tau = \mu \, dv/dz$

where dv/dz is the vertical velocity gradient at depth z, and μ is the dynamic viscosity. Viscous stress causes a parabolic velocity profile in laminar flow with zero velocity at the bed. In turbulent flow, the equation for shear stress must be modified to include an eddy viscosity (ε) term:

$\tau = (\mu + \varepsilon) \, dv/dz$

Because $\varepsilon > \mu$, turbulent flow exerts larger shear stresses than does laminar flow, the viscous component can usually be ignored. Turbulent flow is complex and representative values of eddy viscosity and the velocity gradient difficult if not impossible to obtain. Consequently, a relatively simple model of shear stress is often applied. An estimate of the average boundary shear stress (τ_o) exerted by the fluid on the bed is:

$\tau_o = \gamma Rs$

where γ is the specific weight of water, R is hydraulic radius and s is slope. Derived from a consideration of the conservation of linear momentum, this quantity is a spatial average and does not necessarily provide a good estimate of bed shear at a point.

The forces acting on a non-cohesive particle lying on the bed of a flowing stream include hydrodynamic lift, hydrodynamic drag, and the submerged weight, as seen in Figure 7.3. The drag is in the direction of the flow and the lift is normal to the flow. The hydrodynamic drag may be expressed as $c_1 \tau o d^2$, where c_1 is a constant, τo is bed shear stress or unit of tractive force, d is the grain diameter, and $c_1 d^2$ is the effective surface area upon which the shear stress is exerted. The slope angle of the bed surface in Figure 7.3 is designated as ϕ. The angle θ is the angle of repose between the grains. At the threshold of movement, the resultant of these two forces is along the direction of the friction angle. The ratio of forces on the grain acting parallel to bed to those acting normal to the bed is equal to tan θ (W is the submerged particle weight):

$$\tan\theta = \frac{\text{Drag force} + W \sin\phi}{W \cos\phi}$$

Incipient Motion

Bed erosion

As the flow over a surface of non-cohesive bed material increases, a condition is reached when the forces tending to move a particle are in balance with those resisting motion. This is referred to as the threshold state. Two related approaches are discussed herein, initial movement being specified in terms of either a critical shear stress (τ_{cr}), or a critical velocity (v_{*r}). An alternate approach not discussed is based on the lift force.

The critical shear stress (τ_{cr}) can be defined by equating the applied forces to the resisting forces. For spherical grains of diameter d and density ρ_s on a flat bed, equating the moments of forces acting about a downstream contact point gives

$\tau_{cr} = \eta \, g \, (\rho_s - \rho) \, \pi/6 \, D \tan\phi$

An alternative approach defines the critical condition in terms of velocity rather than shear stress. Smaller particles in interstices of the bed also reduce the shear stress needed to initiate motion of the larger particles. The same basic trends are revealed within either approach; medium sand (0.25-0.5 mm) is the most easily eroded fraction, higher velocities being required to set both coarser and finer grains in motion. Table 2.9 provides limiting shear stress and velocity as a function of sediment size. The V_{*c} term is the critical shear velocity, and is equal to:

$$V_{*c} = \sqrt{gR_hS_f}$$

These approaches have important limitations. They do not address the variability of either flow conditions near the stream bed or bed material characteristics. Short term pulses in the flow can give rise to instantaneous stresses of at least three times the average, so that particles may be entrained at stresses much lower than predicted. Natural bed material is neither spherical nor of uniform size. Larger particles may shield smaller ones from direct impact so that the latter fail to move until higher stresses are attained. For a given grain size, the true threshold criterion may vary by nearly an order of magnitude depending on the bed gradation. In addition to the drag forces acting roughly parallel to the bed, the lift force is normal to the bed, which may be able to entrain particles irrespective of the magnitude of the drag forces, complicating the prediction of bed erosion.

Table 2.9 Limiting shear stress and velocity.

Class name	d_s (in)	f (deg)	t_{*c}	t_c (lb/sf)	V_{*c} (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	4.36
Large	>40	42	0.054	18.7	3.08
Medium	>20	42	0.054	9.3	2.20
Small	>10	42	0.054	4.7	1.54
Cobble					
Large	>5	42	0.054	2.3	1.08
Small	>2.5	41	0.052	1.1	0.75
Gravel					
Very coarse	>1.3	40	0.050	0.54	0.52
Coarse	>0.6	38	0.047	0.25	0.36
Medium	>0.3	36	0.044	0.12	0.24
Fine	>0.16	35	0.042	0.06	0.17
Very fine	>0.08	33	0.039	0.03	0.12
Sands					
Very coarse	>0.04	32	0.029	0.01	0.070
Coarse	>0.02	31	0.033	0.006	0.055
Medium	>0.01	30	0.048	0.004	0.045
Fine	>0.005	30	0.072	0.003	0.040
Very fine	>0.003	30	0.109	0.002	0.035
Silts					
Coarse	>0.002	30	0.165	0.001	0.030
Medium	>0.001	30	0.25	0.001	0.025

Bank erosion

The bank material of natural channels is more variable than the bed material. Most channel banks possess some degree of cohesion because of finer material, so that the analysis of bank erosion is not a simple extension of the non-cohesive bed case with a downslope gravity component added. A further complication is provided by vegetation, whose root system can reinforce bank material and increase erosion resistance. Factors influencing bank erosion are summarized in Table 2.10.

Table 2.10 Factors influencing bank erosion.

Factor	***Relevant characteristics***
Flow properties	Magnitude, frequency and variability of stream discharge; Magnitude and distribution of velocity and shear stress; Degree of turbulence
Bank material composition	Size, gradation, cohesion and stratification of bank sediments
Climate	Amount, intensity and duration of rainfall; Frequency and duration of freezing
Subsurface conditions	Seepage forces; Piping; Soil moisture levels
Channel geometry	Width and depth of channel; Height and angle of bank; Bend curvature
Biology	Type, density and root system of vegetation; Animal burrows
Anthropogenic factors	Urbanization, land drainage, reservoir development and boating

The magnitude and frequency of bank erosion are highly variable because of the large number of factors involved. Correlations between flow volume and amount of erosion tend to be poor. Multi-peaked flows may be more effective than single flows of comparable or greater magnitude because of the increased incidence of bank wetting. Flows with long durations often have a more significant affect on erosion than short-lived flows of higher magnitude. Sites experiencing the same flow and meteorological conditions can show considerable variation in the amount of bank erosion because of variances in non-hydraulic parameters. The local site characteristics that appear to have a major influence on the spatial distribution of erosion are bank material composition, the degree of flow asymmetry and channel geometry. Coarser, sandy materials are more liable to erosion than are those with a high silt-clay content. In composite banks, stability is governed by the strength of the weakest material since its removal will eventually produce failure in the rest of the bank.

Sediment Continuity

Sedimentation embodies the processes of erosion, entrainment, transportation, deposition, and compaction of sediments. Like water, sedimentation processes must obey the laws of continuity. Within a particular reach the sediment entering the upper end is either transported through on its own, deposits within the reach or is transported and augmented with additional sediments eroded from the bank and bed. In the first case the bed remains stable; in the latter two, the bed is aggradational or degraditional, respectively. The terms aggradation and degradation generally refer to trends in the location and behavior of the stream bed profile. An aggrading stream is one in which the bed profile is tending to become steeper, whereas the converse is true for a degrading stream. True aggradation or degradation is usually associated with observed changes over time, not normal fluctuation within a dynamic system. The fact that a reach of a river scours during a flood event does not make it a degrading reach.

Classification of Transport

Particles move in a channel bottom in a variety of ways, are measured using different techniques, and are grouped for analyses in differing ways. Because of these variations, sediment transport terminology can sometimes be confusing. It is important to define some of the more frequently used terms, and the following definitions below follow the most accepted convention.

1) Sediment Discharge (or Sediment Load): The quantity of sediment that is carried past any cross section of a stream in a unit of time.

2) Bed-Material Discharge (or Bed-Material Load): The part of the total sediment discharge that is composed of sediment sizes found in the stream bed.

3) Wash Load: Part of the total sediment load that is comprised of particle sizes finer than those found in the stream bed.

4) Bed Load Discharge (or Bed Load): The portion of the total sediment load that moves on or near the stream bed by saltation, rolling, or sliding in the bed layer.

5) Suspended Sediment Discharge (or Suspended Load): Portion of the total sediment load that is transported in suspension by turbulent fluctuations within the body of flowing water.

6) Suspended Bed Material Load: The portion of the bed material load that is transported in suspension in the water column. The suspended bed material load and the bed load comprise the total bed material load.

7) Measured Load: Portion of the total sediment load that is obtained by the sampler in the sampling zone.

8) Unmeasured Load: Portion of the total sediment load that passes beneath the sampler, both in suspension and on the bed. With typical suspended sediment samplers this is the lower 0.3 to 0.4 feet of the vertical.

The above terms can be combined in a number of ways to provide meaningful measures of sediment load in a stream. Not all terms are compatible; however, the combination of the following terms are those considered acceptable:

Total Sediment Load = Bed Material Load + Wash Load
Total Sediment Load = Bed Load + Suspended Load
Total Sediment Load = Measured Load + Unmeasured Load
Bed Material Load = Measured Load + Unmeasured Load

Streambank Failure Mechanisms

Banks fail and erode because they exist in a dynamic environment that is constantly subjected to various forces. River banks fail in one of four ways:

- Hydraulic forces remove erodible bed or bank material,
- Geotechnical instabilities result in bank failures,
- Mechanical actions cause a reduction in the strength of the bank, or
- A combination of the above factors causes failure.

These modes of failure have distinct characteristics. An investigation must be conducted to determine the specific mode of failure because this is indicative of the problem.

Hydraulic Erosion

When bank erosion occurs primarily from the forces of flowing water, the mode of failure is hydraulic. This is not generally the only mode of failure, but hydraulic forces play a role in nearly all types of bank failure.

Six categories of hydraulic bank erosion process as may be identified, and each is discussed in more detail below:

- fluvial entrainment by water flowing parallel to the bank,
- fluvial entrainment by water impinging against the bank,
- boatwash,
- wind-waves,
- rills and gullies, and
- piping.

Fluvial entrainment by water flowing parallel to the bank causes erosion by removal of soil particles when fluid shear stresses exerted on the bank are greater than the shear resistance of the bank material. Fluvial entrainment is a common cause of bank retreat, and indicates that the bank material is unable to withstand the near-bank velocities imposed by flow in the channel. To be successful, any protection scheme must deal with this imbalance either by reducing velocities or by increasing bank erosion resistance. This imbalance occurs mainly during high, in-bank flows, is usually concentrated on the lower third of the bank, and is characterized by a lack of bank vegetation and no mass wasting.

Impinging flow attacks the bank at an angle to the long-stream direction. Erosion can occur at a range of discharges because of the intense turbulence generated when impinging flow strikes the bank. Impinging flow usually occurs at tight meander bends that are close to cut-off and around flow obstacles such as bars, fallen trees and some hydraulic structures. Impinging flow erosion often indicates poor channel alignment and may require a realignment as only the heaviest forms of bank protection can withstand this type of erosive attack. Impinging flow is differentiated from, parallel flow by channel alignment. It is important to note that flow alignment varies with discharge and field observations of bank failures should include an assessment of flow angle at a variety of flow conditions.

A variety of disturbances are involved in boat wash including bow and stern waves, drawdown, displacement, propeller jet and return currents. Waves and currents drive erosion due to high velocities and shear stresses while rapid water-level changes may induce fluctuating pore water pressures that weaken the bank material to promote bank failure. Boat wash can be a primary cause of bank erosion. Its severity increases non-linearly with boat speed, but is also affected by hull design, waterway size and geometry, and the proximity of the sailing line to the bank. By initiating erosion that destroys riparian vegetation, boat wash can open the bank surface to a wide variety of secondary erosion processes and weakening factors that accelerate the rate of retreat. It can be managed by reducing boat speeds, altering sailing lines and/or legislating hull redesign as well as local bank protection.

Wind-waves cause erosion in much the same way as boat-generated waves. They are a primary cause of erosion only on large rivers. Wind-wave erosion can generate serious secondary erosion to perpetuate a problem where other more aggressive processes or mechanisms have removed the protection afforded by natural vegetation.

Rills and gullies are channels cut into the bank by overland draininage. They form where surface drainage concentrates at a local low point or where vegetation has been removed, exposing the underlying soils. Rills and gullies roughen the bank face, generating turbulence and enhancing flow erosion. Gullies also present a hazard to people and stock moving along the bank top.

Piping occurs when ground water draining through the bank entrains and removes soil particles. The nature of the process depends on the seepage pressure, the chemistry of the pore water and the mineralogy of the soil. It is most prevalent where seepage within the bank is concentrated, such as where a sandy layer is sandwiched between less-permeable clay layers, or where poorly-designed bank work impedes free drainage. Piping may produce either pipe-shaped cavities extending back into the bank or a notch in the bank profile just above the normal low-water stage, depending on the stratigraphy of the bank. The significance of piping is that it operates out of sight, within a bank, to remove material, weaken the bank and reduce its stability. The threat posed by existing or potential piping is often overlooked in the design of protection works, leading to their failure. If piping is suspected, a geotextile or natural filter must be used to retain the soil while ensuring adequate drainage to disperse pore water pressure.

Geotechnical Failure

Several different types of mass failure can occur in banks. These include sliding along a deep failure surface, shallow slips, and block failures. Factors affecting mass failures include soil type, bank geometry, hydrology, surcharge, and vegetation. Banks may fail suddenly, particularly if there is active surface erosion or toe scour, or sudden additional loading is applied to the bank. By far, the greatest number of river bank failures occur during heavy rains or high river stages and shortly afterwards.

Figure 2.9 shows examples of the different failure types. Standard textbooks on geotechnical engineering are helpful in understanding the basic mechanics of failure; however, not all the factors pertinent to river banks are likely to be covered. Seven categories of mechanism responsible for bank collapse may be identified:

- shallow slideing,
- rotational slip,
- slab-type failure,
- cantilever failure,
- soil fall,
- dry granular flow, and
- wet earth flow.

Shallow sliding occurs when a layer of bank material slides along a failure plane parallel and just below the bank surface. This failure mechanism is common in soil of low cohesion and is triggered when the bank angle exceeds the angle of internal friction of the bank material. Slides are caused by flow, boatwash or windwave erosion of the lower bank that undercuts the upper bank, or by weakening factors that reduce the friction angle. Shallow slides destroy the surface of the bank and deliver considerable quantities of disturbed, loose sediment to the toe area, where the bank is vulnerable to erosion by currents and waves. The significance of shallow slide as a failure mechanism is that it can be triggered by processes operating either on or within the bank, and it carries away the surface material, including vegetation and any natural or artificial armour layer, which reduces the erosion resistance of the bank.

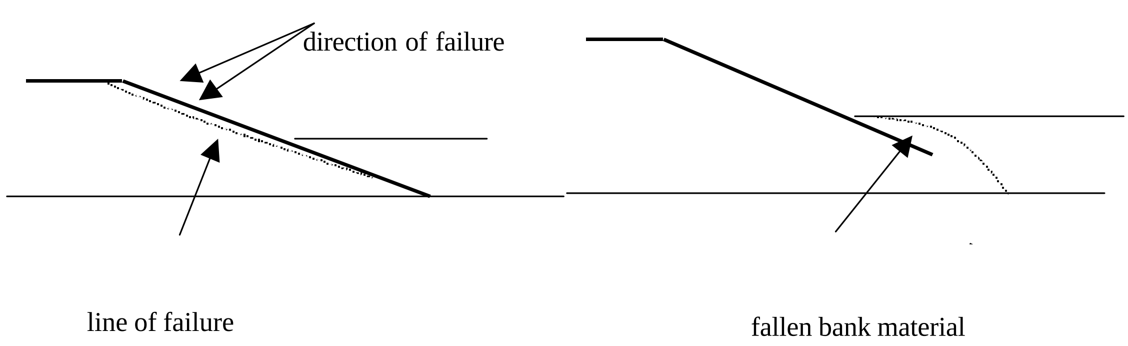
A rotational slip is a deep-seated movement of all or part of the bank profile in which a block of soil slips downward and outward along a curved failure surface. Curvature of the slip surface produces back-tilting of the failure block towards the bank. It occurs in high banks with relatively gentle slopes (less than 60°) formed in strongly cohesive soils. Failure is triggered by toe scour and/or adverse drainage within the bank. High positive pore water pressures generated following a high flow stage that has saturated the bank contribute to failure. The failure block may remain semi-intact and, while in position at the toe, acts as temporary toe protection. Rotational slip is a severe form of instability that involves the movement of a large volume of soil, total disruption of the bank profile, destruction of any vegetation and structures on the bank and rapid retreat of the bankline. Rotational slips are a definite sign of mass instability and the bankline cannot possibly be stabilized unless such instability is eliminated. This will require heavy intervention through re-profiling and improved drainage.

Slab-type failure occurs when a block or slab of soil topples forward into the channel. Often deep tension cracks separate the failure block from the rest of the bank. These failures are common on low, steep (greater than 60°) banks formed in moderately cohesive soils. Failure is triggered by toe scour, tension cracking and/or adverse drainage within the bank that generates high positive pore water pressures. The failure block usually disintegrates to produce a loose talus slope that acts as temporary toe protection. Like rotational slip, slab-type failure is a severe form of instability. The significance of slab-type failures is that they are a definite sign of mass instability, and the bankline cannot possibly be stabilized unless such instability is eliminated. This will require heavy intervention through re-profiling and improved drainage to increase bank stability.

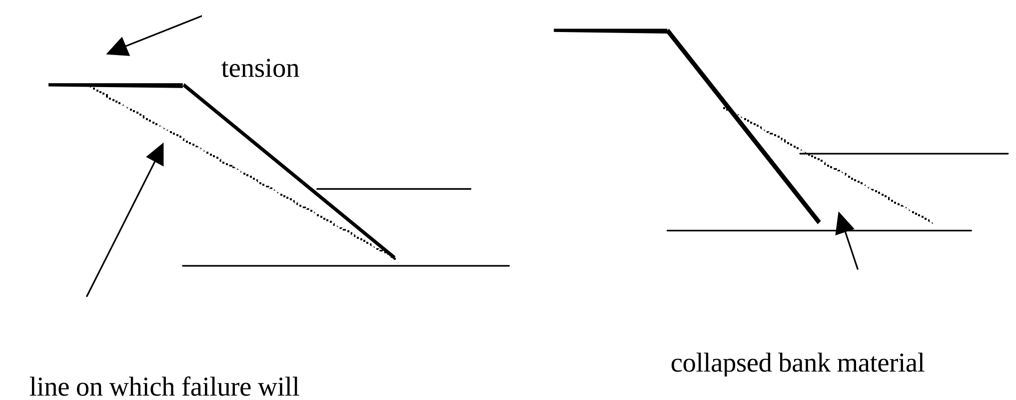
Cantilever failure occurs when an overhanging block collapses into the channel. Overhangs are found in layered banks where a resistant, cohesive or root-bound layer overlies an erodible, non-cohesive layer. Undermining by flow or wave erosion leaves an overhang which falls into the channel when its weight becomes limiting. Failed blocks may remain intact to provide temporary toe protection, but are usually removed by the flow to allow renewed undercutting. Cantilever failures indicate active undercutting and the presence of a weak layer within the bank. Both these facts indicate that serious, sustained bankline retreat will probably continue at the site unless steps are taken to prevent undercutting by reducing current and wave action or to reduce the erodibility of the weak layer.

Figure 2.9 Failure mechanisms (following pages):

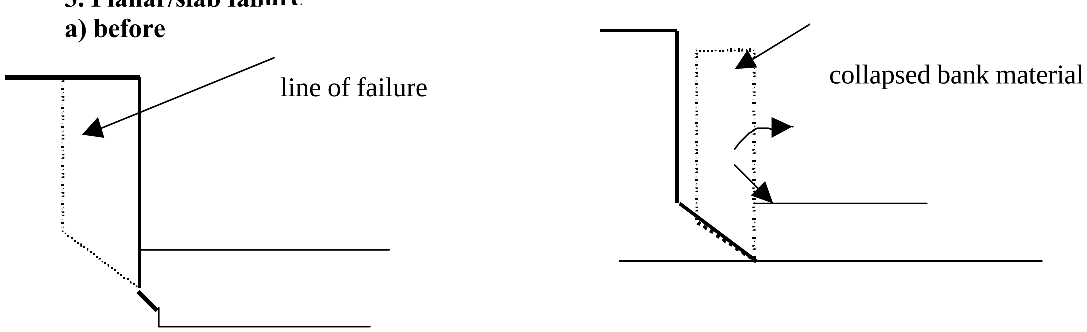
1. Shallow failure
a) before **b) after**



2. Planar failure
a) before **b) after**



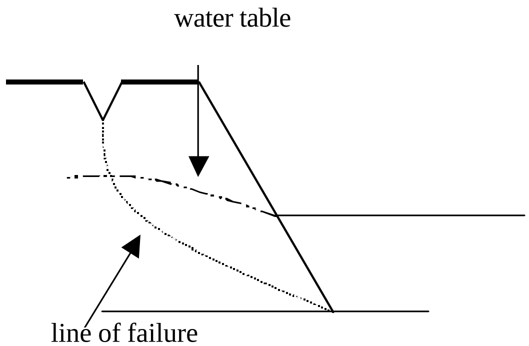
3. Planar/slab failure
a) before **b) after**



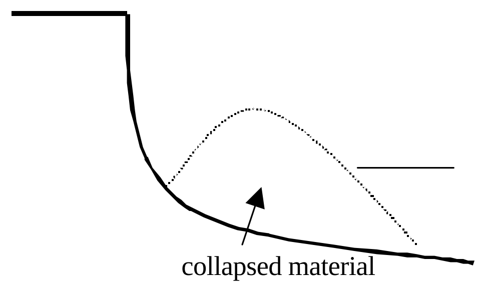
* Collapsed material will slide and/or rotate forward.

4. Rotational failure in homogeneous material

a) before

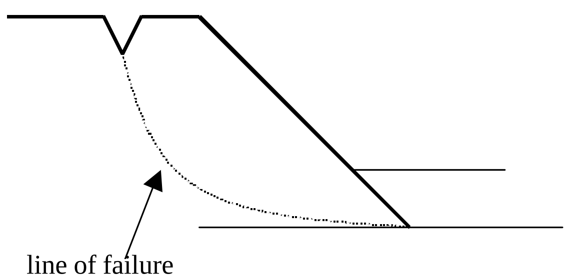


b) after

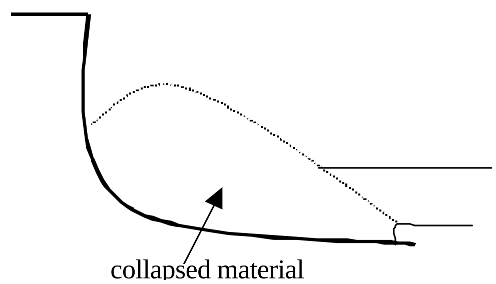


5. Rotational failure / weak zone

a) before

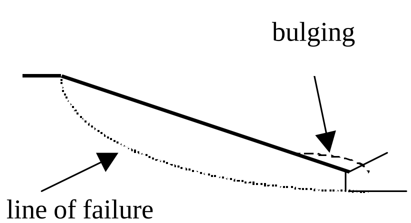


b) after

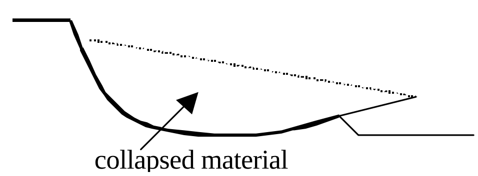


6. Massive rotational failure

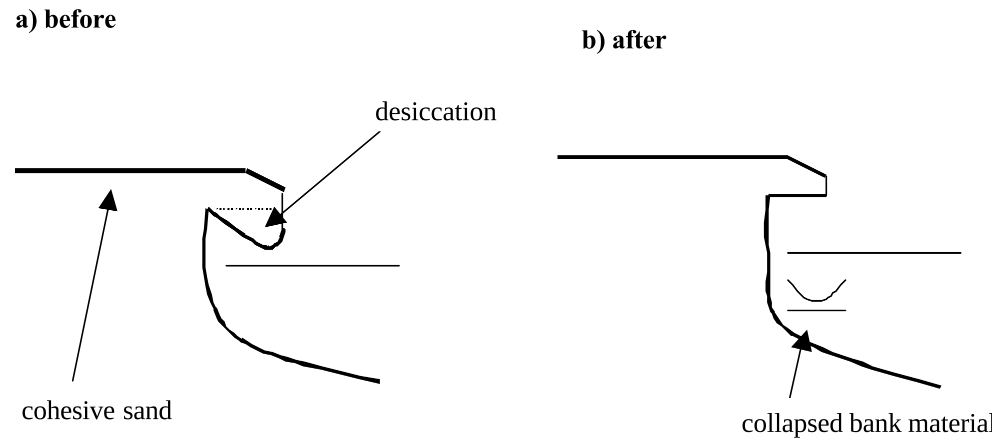
a) before



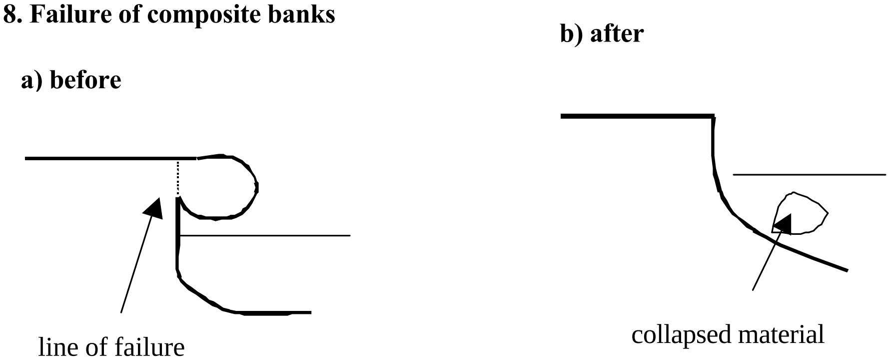
b) after



7. Failure of composite bank



8. Failure of composite banks



Soil fall occurs when individual particles or aggregates of particles fall directly into the channel from nearvertical or undermined banks. It often follows weakening by desiccation, saturation or frost action on an unvegetated bank face. Soil fall is an important contributor to bank retreat on steep, unvegetated banks formed in weakly cohesive soils. It delivers loose sediment to the bank toe, where this material is vulnerable to erosion if the bank is being eroded, or may form a spending beach or wet berm. Soil fall is limited to very steep banks subject to erosion by flow, boatwash or piping processes. It adds to but does not initiate bank retreat and is simply eliminated by regrading the bank to a lower angle and re-vegetating the bank surface.

Dry granular flow is an avalanche of dry, granular bank material. It occurs on the upper, unsubmerged part of a well-drained, non-cohesive bank that is close to the angle of repose due to undercutting by current or wave erosion. The result is that retreat of the bank edge occurs at a rate matched to that of flow and wave erosion of the lower bank.

Dry granular flow as a failure mechanism is limited to banks that are truly noncohesive. In practice, most bank materials behave as if they have some cohesion due to the reinforcing effects of pore water suction or the roots of bank vegetation.

Wet earth flow is a total loss of strength in a section of bank due to saturation and strong seepage pressures. The soil is liquefied and flows out from the bank in a low-angle failure. Such failures occur where a concentration of subsurface flow leads to water logging and high positive pore water pressures. Earth flows can occur on banks at low angles and jeopardize vegetation and structures on or behind the bankline. The failed material has very little strength and is easily eroded by current and wave action. The significance of wet earth flows is that they indicate serious instability due to adverse or interrupted drainage within the bank. Any attempt to stabilize the bankline must involve improving stability by draining the bank to dissipate positive pore water pressures while preventing soil loss by piping or weakening by leaching.

Weakening Actions

Seven categories of factors responsible for decreasing the erosion resistance and mechanical stability of a bank may be identified:

- leaching,
- trampling,
- destruction of riparian vegetation,
- mechanical damage,
- positive pore water pressures,
- desiccation, and
- freeze thaw.

Leaching leads to weakening of the bank through the reduction of cohesion that occurs when clay minerals are removed by solution in groundwater seeping through the bank. This process can seriously reduce both the mechanical strength of the bank material and its erosion resistance, leading to bank instability and erosion by waves and currents that would not be able to erode unleached bank materials. The vulnerability of a bank to weakening by leaching depends on its clay mineralogy and the chemistry of the pore water. In this respect, pollution can be a factor, as polluted groundwater may cause an increase in leaching. The significance of leaching to bank stability and erodibility should not be under-estimated. Banks which depend on cohesion for their stability and which contain dispersive clays are vulnerable to destabilization by leaching and this must be recognized and accounted for in the selection of appropriate remedies to bankline erosion.

Trampling weakens the bank through the destruction of the soil fabric. This fabric consists of the structure of aggregates of primary soil particles and the electrochemical bonds which bind them together to give the soil cohesion. Trampling breaks these bonds and crushes the structure to produce an amorphous soil mass. Trampling is a serious weakening factor because the erosion resistance and stability of many soils rely almost entirely on the soil fabric. Also, trampling reduces infiltration capacity, leading to increased overland flow. Trampling by people and animals may be a major factor in reducing the erosion resistance and stability of a stream bank. It may allow bank erosion and failure to occur at locations which would be entirely stable if the bank were untrampled.

Riparian vegetation is vulnerable to damage from a variety of natural processes and human actions. Erosion that scours or undermines the roots will often kill vegetation, while mass failure uproots and relocates it, generally with fatal results. Human actions, including unsympathetic channel maintenance, trampling and overgrazing by farm stock and cutting by anglers, can severely damage or remove vegetation completely. Riparian vegetation plays a crucial and integral role in determining the erosion resistance and mechanical stability of stream banks. This role is complex and the sensitivity of a bank to destabilization due to the disruption or removal of vegetation is difficult to predict. However, numerous case studies demonstrate that destruction of riparian vegetation can accelerate bankline retreat rates dramatically. The significance of riparian vegetation must be recognized. It is an integral component of the river bank system and its destruction may be a crucial factor in weakening a bank and allowing erosion to begin. If trampling, overgrazing or inappropriate maintenance have led to destruction of the riparian corridor, its reestablishment should be a high priority in any scheme for bank management or erosion control.

Mechanical damage to banks formed in alluvial materials occurs when unusual forces are applied to the bank surface. Examples include boat mooring (hull impacts, driving stakes, propeller wash), cutting of access ramps for farm stock at watering points, and the digging of embayments at fishing pegs used in angling competitions. Damage tends to be of limited extent, but it can trigger impinging flow that generates rapid development of embayments in the bankline. Damaged areas present footholds for erosion and failure to begin to attack otherwise stable banks. Instability may spread outwards to affect intervening, natural reaches, leading to disruption of the entire bankline. The significance of mechanical damage is that it leads to localized erosion that has the potential to spread widely. The sensitivity of a reach to destabilization in this way is difficult to predict. Hence, it is highly undesirable that mechanical damage to natural banks be allowed.

Positive pore water pressures occur when drainage of water through the bank is restricted. By reducing the effective strength of the bank material, positive pore pressures weaken the bank, increasing the probability of block failure or, in extreme cases, leading to liquefaction and a wet earth flow. Positive pore water pressures are most likely when the water surface elevation in the channel falls rapidly. This occurs during drawdown following a flood and if boatwash causes intense waves or surface drawdown alongside the hull. The significance of positive pore water pressures in weakening stream banks is widely recognized. Poorly drained banks are often observed to collapse during drawdown after flood peaks, and on regulated rivers, care must be taken to avoid generating rapid water-level changes. On navigable watercourses, drawdown impacts should be avoided by limiting boat speeds and keeping the sailing line well away from the banks.

Desiccation occurs when a soil shrinks and cracks on drying to the point that electro-chemical bonds between particles and aggregates are broken. During the summer, the face of an unvegetated bank with a southern exposure may reach very high temperatures, leading to intense desiccation. The loosened particles and aggregates are susceptible to erosion by currents, waves and mechanical damage, leading to significant bank retreat. The significance of desiccation is limited to unvegetated river cliffs and other exposed banks, but is not itself a factor responsible for initiating erosion. However, erosion may occur where the effects of riparian vegetation in shading and reinforcing the soil surface are absent.

Freezing and thawing of water causes it to expand and contract. In the case of pore water in a bank, this can weaken the bank through heaving of the soil fabric. At the face of a bare soil face, needle ice growth can weaken or detach soil particles and aggregates that fall off the bank during the subsequent thaw. Freeze/thaw can be very effective in loosening particles and crumbs of soil al the surface of an unvegetated bank face, making them susceptible to erosion by river flow, boatwash, windwaves or rilling/gullying.

Combined Causes

Bank problems rarely result from the operation of a single process of erosion or mechanism of instability. In fact, bank retreat is usually the result of complex interactions between a number of processes and mechanisms that act on the bank either simultaneously, or sequentially. Bed degradation leading to an over-steepening of the banks and a subsequent geotechnical failure is an example. Another is when successive slip plane failures occur on a geotechnically unstable bank and hydraulic forces erode mass wasted material at the toe, which is resisting further slips.

Table 2.11 Classification of Erosion Processes

Erosion process	Description	Impacts on Bank Retreat	Significance
Parallel flow (fluvial entrainment)	Soil is detached and carried away by flow parallel to the bank.	This is a primary cause of bank retreat. It often drives rapid bankline retreat and planform evolution.	Indicates that bank materials cannot withstand shear stresses exerted by flow along the channel.
Impinging flow (fluvial entrainment)	Soil is detached and carried away by flow striking the bank at an angle to the long-stream direction.	This is a primary cause of bank retreat. It occurs at tight bends and around obstructions to the flow.	Impinging flow is usually a sign of a poor channel alignment or an undesirable obstruction of the flow.
Boatwash	Soil is detached and carried away by waves and currents generated by passing boats.	Boatwash can be a primary cause of bank erosion. It tends to be concentrated on the inside of meander bends and around marinas.	Boatwash erosion due to normal cruising indicates that speed limits are too high. Local protection inside bends and around marinas may be justified.
Wind-waves	Soil is detached and carried away by waves and currents generated by the wind.	Wind-waves are seldom a primary cause of serious erosion on most rivers and inland waterways.	Wind-waves cannot initiate an erosion problem but they may perpetuate one by generating secondary erosion.
Rills & gullies (surface erosion)	The bank is eroded by concentrated surface runoff draining across the bankline.	Serious erosion is usually localized at places where drainage has been artificially funnelled.	Rills and gullies can damage a bank severely by destroying vegetation and removing surface layers.
Piping (seepage erosion)	Subsurface erosion by water draining through the bank.	Piping can open up cavities and notches that can lead to serious and widespread bank retreat in vulnerable soils. schemes.	Piping operates within the bank to erode and weaken it. It is often overlooked in protection.

Table 2.12 Classification of Failure Mechanisms

Failure mechanism	Description	Impacts on bank retreat	Significance
Shallow slide	Shallow seated failure along a shear plane parallel to and just below the bank surface.	Can be a serious form of instability in weakly cohesive bank materials.	Indicates that the bank is too steep to remain stable in its present condition.
Rotational slip	Deep-seated movement of all or part of the bank profile in which a block of soil slips along a curved surface.	A severe type of failure that involves the movement of a large volume of soil and generates serious bankline retreat.	Indicates serious, deep-seated instability that must be eliminated to halt bank retreat. This requires heavy intervention.
Slab failure	Blocks or columns of soil topple forward into the channel, often with deep tension cracks separating the failure blocks from the intact bank.	A severe type of failure that involves the movement of a large volume of soil and generates rapid bankline retreat.	Indicates serious instability due to toe scour, over-steep bank angles and tension cracks. All these must be controlled.
Cantilever failure	Overhanging blocks of soil collapse into the channel by shear, beam or tensile failure.	Cantilevers follow flow, wave or piping erosion of the lower bank.	Indicates active undercutting and presence of a weak, erodible layer.
Soil fall	Soil falls directly into the channel from near-vertical or undermined, cohesive bank face.	Important on unvegetated soil surfaces weakened by desiccation, frost action etc.	Indicates that soil surface is vulnerable to weakening. Surface cover is needed.
Dry granular flow	Avalanching of dry, granular bank material down the upper part of a non-cohesive bank.	A mechanism whereby erosion of the lower bank causes instability of the upper bank and bankline retreat.	Indicates zero operational cohesive strength due to lack of root reinforcement or negative pore water pessures in the bank material.
Wet earth flow	Liquefaction and flow of a section of bank due to saturation and high pore water pressures.	Can result in rapid bankline retreat in zones of strong seepage and poor drainage.	Indicates seepage-related instability and soils prone to liquefaction. Bankline stabilization must include enhanced drainage.

Table 2.13 Classification of Weakening Factors

Weakening factor	Description	Impacts on bank retreat	Significance
Leaching	Reduction of cohesion due to removal in solution of clay minerals by groundwater seepage.	Can seriously reduce both the stability and erosion resistance of the bank.	Indicates that the mineralogy of the soil and the chemistry of pore water are important.
Trampling	Destruction of the soil fabric by crushing under the weight of pedestrians or grazing animals.	Impacts can be severe since the stability and erosion resistance of many banks depends almost entirely on soil fabric.	Indicates that the bank soils arc vulnerable to damage by trampling and that access should be reduced or protection provided.
Destruction of riparian vegetation	Damage or destruction of riparian vegetation by a variety of natural processes and human actions.	Impacts are usually severe as vegetation can play a crucial role in determining the erosion resistance and stability of banks.	Riparian vegetation is an integral component of the bank system. Its destruction is highly undesirable and its conservation should figure in most bank management schemes.
Mechanical damage	Damage of banks formed in alluvial materials by boat mooring, stock access or angling practices.	Damaged areas suffer serious erosion and can generate locally impinging flows that accelerate bankline retreat.	Mechanical damage provides a foothold for erosion on stable banks. In sensitive reaches erosion problems may spread widely.
Positive pore water pressures	Occur when drainage of water through the bank is restricted to allow a build up of seepage pressure.	Can be very effective in weakening the soil to promote failure or liquefaction.	Poorly-drained banks are always likely to fail if high pore water pressures occur.
Desiccation	Cracking and crumbling of a soil due to intense drying that breaks electro-chemical bonds.	Loosens soil crumbs on exposed bank surfaces during hot summers.	Significance is limited to river cliffs and other places with no vegetation.
Freeze/thaw (frost erosion)	Soil particles or aggregates are loosened by freezing and either fall off the bank face during	Freeze/thaw is only significant in a few eroding unvegetated bank faces. It is the flow or boatwash.	Freeze/thaw typically makes a bank more vulnerable to erosion by winter not itself a primary cause of bank retreat.flows.

Streambank Zones

Plants should be positioned in various elevation zones of the bank based on their ability to tolerate certain frequencies and durations of flooding and their attributes of dissipating current- and wave-energies. Likewise, bioengineering fixes should be arranged by zone, which will be discussed below. The zone definitions given below correspond to those used by the U.S. Army Corps of Engineers, Omaha District, and have been used in preparing guidelines for the use of vegetation in streambank erosion control of the upper Missouri River (Logan et al. 1979). These zones are not precise and distinct since stream levels vary daily and seasonally - they are only relative and may be visualized as somewhat elastic depending on the bank geometry. If one carefully copied nature in the planning process, plant species can be chosen that will adapt to that specific zone or micro-habitat. Figure 2.10 illustrates the location of each bank zone for the upper Missouri River example. A description of each and the types of vegetation and appropriate species examples associated with them is given below. This zonal concept can be expanded to other streams to facilitate prescription of erosion control treatment, and plants to use at relative locations on the streambank.

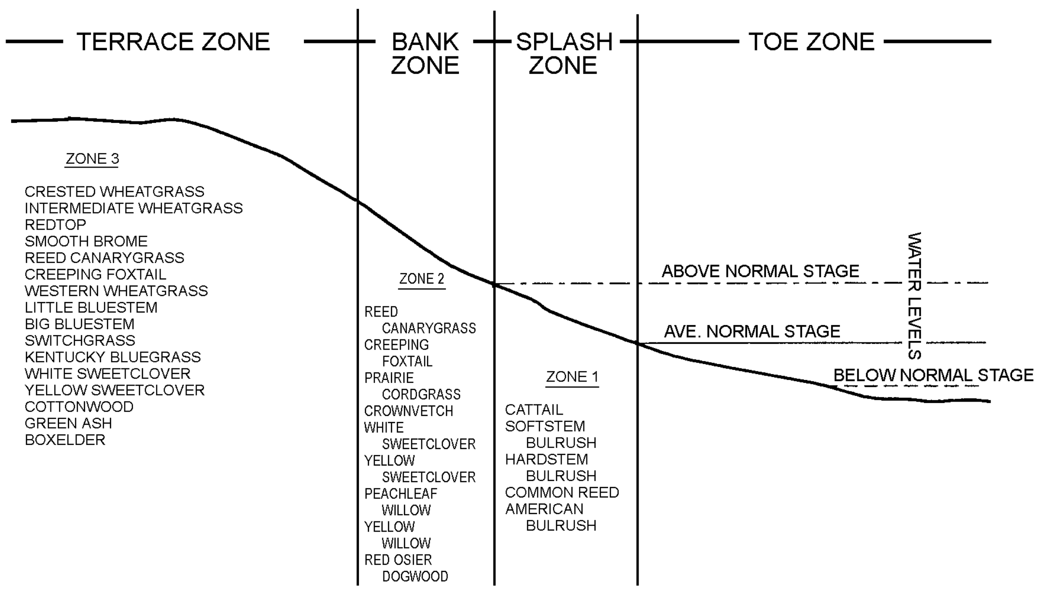


Figure 2.10 Bank zones for upper Missouri River.

Toe zone. That portion of the bank between the bed and average normal stage. This zone is a zone of high stress and can often be undercut by currents. Undercutting here will likely result in bank failure unless preventative or corrective measures are taken. This zone is often flooded greater than 6 months of the year.

Figure 2.10 illustrates the plant species prescribed for each streambank zone on the upper Missouri River, except for the toe zone. The toe zone would likely have to be treated by some hard material, such as rock, stone, log revetments, cribs, or a durable material such as a geotextile roll (to be discussed later).

<u>Splash zone.</u> That portion of the bank between normal high-water and normal low-water flow rates. This and the toe zone are the zones of highest stress. The splash zone is exposed frequently to wave-wash, erosive river currents, ice and debris movement, wet-dry cycles, and freezing-thawing cycles. This section of the bank would be inundated throughout most of the year (at least 6 months/year), but note that a large part of this inundation may occur in the dormant season of plants. The water depths will fluctuate daily, seasonally, and by location within the splash zone.

Only herbaceous emergent aquatic plants like reeds, rushes, and sedges are suggested for planting in the splash zone (Figure 2.10). These types of plants can tolerate considerable flooding and are more likely to live in this zone. They possess aerenchyma, cells with air spaces, in roots and stems that allow the diffusion of oxygen from the aerial portions of the plant into the roots (Mitsch and Gosselink, 1986). Therefore, they can extend roots into deeper water than many other types of plants, such as woody plants. Reeds, such as common reed (*Phragmites australis*), and sedges, such as bulrushes (*Scirpus* spp.), also protect streambanks in various ways. Their roots, rhizomes, and shoots bind the soil under the water, sometimes even above the water (Seibert 1968). In the reed zone, as Seibert (1968) defines it, they form a permeable underwater obstacle which slows down the current and waves by friction, thereby reducing their impact on the soil. Active protection of the bank can be ensured by reeds only in an area that is constantly submerged (Seibert 1968).

It should be mentioned that common reed is often considered a pest in the U.S., where it has been observed as a monotypic plant that does not offer habitat diversity. The authors would submit that this is true where there is not much of an elevation and hydrologic gradient. In other words, on shallow flats that become periodically inundated, it can thrive. However, when it is on a shoreline and becomes inundated over about 18 inches, it is often replaced by other more water tolerant species. One should use caution on where this plant is used and match it to one's objectives.

Various wetland grasses, sedges, and other herbs were used in this zone as a part of a coir geotextile roll in an urban park setting in Allentown, Pennsylvania. The main vegetative components of erosion control of the stream embankment are: lake sedge (*Carex lacustris),* stubble sedge (*C. stipata),* and woodland bulrush (*Scirpus sylvaticus*). Other minor components used for diversity and color included: rice cut-grass (*Leersia oryzoides*), other sedges (*C. lata, C. lanuginosa, C. hysterina, and C. prasina)*, softstem bulrush (*Scirpus validus),* blue flag iris (*Iris versicolor),* and monkey flower (*Mimulus ringens*). The latter two species were provided primarily for additional diversity and color (Siegel, 1994a). Siegel reported that these plants, along with bioengineering methods such as the coir roll, stabilized a streambank that was subjected to storm events. In fact, the methods were designed to accentuate and enlarge the existing floodplain to act as a buffer zone for floods associated with storms greater than the 25-yr event (Siegel, 1994b). The vegetation list above only gives one example of types of species that were used for erosion control in the splash zone, i.e., flood-tolerant and fast growing grasses and sedges. Care should be exercised in selecting species that are adapted to the project's geographic area. Local university botanists and USDA Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) district personnel can be consulted for suitable species.

Herbaceous emergent aquatic plants, like those shown in Figure 8, must be used on a streambank that has a geometric shape conducive to such plants. Caution must be used on streams that have heavy silt loads that could suffocate plants. These plants must grow in fairly shallow water, from +45 to -152 cm (Allen et. al, 1989). Sometimes, it is impossible or impractical to find or shape a stream to match those conditions. Then, flood-tolerant woody plants, like willow (*Salix* spp.*)*, dogwood (*Cornus* spp.), and alder (*Alnus* spp.) are used in the splash zone. Again, a good rule of thumb is to look at the natural system and observe what is growing there and try to duplicate it.

<u>*Bank zone.*</u> That portion of the bank usually above the normal high-water level; yet, this site is exposed periodically to wave-wash, erosive river currents, ice and debris movement, and traffic by animals or man. The site is inundated for at least a 60-day duration once every two to three years. The water table in this zone frequently is close to the soil surface due to its closeness to the normal river level.

In the bank zone, both herbaceous (i.e., grasses, clovers, some sedges and other herbs) and woody plants are used. These should still be flood tolerant and able to withstand partial to complete submergence for up to several weeks. Allen and Klimas (1986) list several grass and woody species that can tolerate from 4 to 8 weeks of complete inundation. This list should not be considered exhaustive, however. Whitlow and Harris (1979) provide a listing of very flood-tolerant woody species and a few herbaceous species by geographic area within the United States that can be used in the bank zone.

Skeesick and Sheehan (1992) report on several other herbaceous and woody plants that can withstand tens of feet of inundation over 3 to 4 months in two different reservoir situations in Oregon. These same species are often found along streambanks. Local university botanists and plant material specialists within the NRCS should be consulted when seeking flood-tolerant plants. Various willows can be used in this zone, but they should be shrublike willows such as sandbar willow (*S. exigua*) and basket willow (*S. purpurea* var. *nana*). Edminster et al. (1949) and Edminster (1949) describe successful use of basket willow for streams and rivers in the Northeast. Shrub-like willow, alder, and dogwood species have been used in Europe successfully (Seibert 1968). Red-osier dogwood (*Cornus stolonifera*) and silky dogwood (*C. amomum*) also have been used in the Northeast (Edminster et al. 1949 and Edminster 1949). Seibert (1968) notes that in periods of high water, the upper branches of such shrubs reduce the speed of the current and thereby the erosive force of the water. The branches of these have great resilience, springing back after currents subside.

<u>*Terrace zone.*</u> That portion of the bank inland from the bank zone; it is usually not subjected to erosive action of the river except during occasional flooding. This zone may include only the level area near the crest of the unaltered "high bank" or may include sharply sloping banks on high hills bordering the stream.

The terrace zone is less significant for bank protection because it is less often flooded, but can be easily eroded when it is flooded if vegetation is not present. Vegetation in this zone is extremely important for intercepting floodwaters from overbank flooding, serving to reduce super-saturation and decrease weight of unstable banks through evapotranspiration processes and for tying the upper portion of the streambank together with its soil-binding root network. Coppin and Richards (1990) provide a detailed explanation of plant evapotranspiration, but summarize by saying, "Apart from increasing the strength of soil by reducing its moisture content, evapotranspiration by plants reduces the weight of the soil mass. This weight reduction can be important on vegetated slopes where the soil may be potentially unstable."

As denoted in Figure 2.10, the terrace zone can contain native grasses, herbs, shrubs, and trees that are less flood tolerant than those in the bank zone, but still somewhat flood tolerant. The tree species also become taller and more massive. Trees are noted for their value in stabilizing banks of streams and rivers (Seibert 1968; Leopold and Wolman, 1957; Wolman and Leopold, 1957; Lindsey et al. 1961; and Sigafoos 1964). The trees have much deeper roots than grasses and shrubs and can hold the upper bank together. The banks of some rivers are not eroded for durations of 100 to 200 years because heavy tree roots bind the alluvium of floodplains (Leopold et al. 1957; Wolman and Leopold 1957; and Sigafoos 1964). A combination of trees, shrubs, and grasses in this zone will not only serve as an integrated plant community for erosion control, but also improve wildlife habitat diversity and aesthetic appeal.

3 Ecological Functions Of Streams

Chapter Overview

This chapter presents a brief overview of some ecological considerations associated with stream restoration and management projects. The primary intent of the chapter is to establish that streams perform a variety of important functions and that the ability of a stream system to support these functions depends upon its physical condition. The authors concede that it is impossible in this text to address even the most basic of ecological considerations associated with restoration and management projects, but hope to impart upon the readers the importance of considering and evaluating stream ecology and function for all projects.

Stream Form and Function

In any ecosystem, there is a set of complex relationships between numerous dependent variables that dictate the physical, biological and chemical character of the environment. Changes to any one variable, whether induced by nature or as a result of man's activities, cause the system to respond in ways that are not altogether predictable, and create changes in all other variables. Because of the interrelationship of these variables, it is often difficult to assess the performance and impact of proposed actions. A basic understanding of fluvial processes, geomorphology, hydrology, hydraulics, stream ecology, and natural and anthropogenic impacts is needed to undertake these analyses.

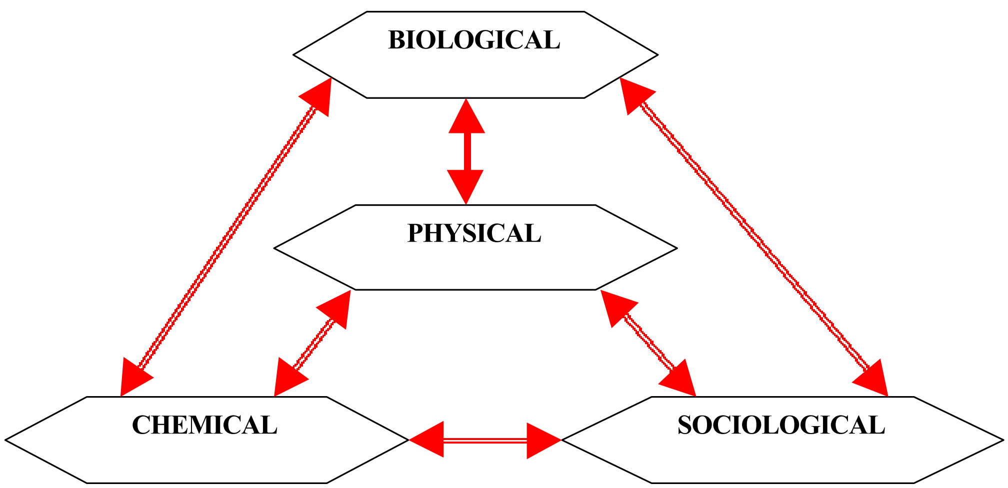


Figure 3.1 Ecosystem Relations

Structural Characteristics

The function and ecological character of a stream or riparian system are closely related to the system's structural characteristics. The following list describes some of the structural characteristics that play an important role in defining ecological function.

1. **Hydrology and Hydraulics**, including quantity of discharge on annual, seasonal, and episodic basis; timing and duration of discharge; surface flow processes, including velocities, turbulence, shear stress, bank/stream storage, and exchange processes; tides; ground water flow and exchange processes; retention times; particle size distribution and quantities of bed load and suspended sediment; and sediment flux.

2. **Water Quality** including measures of dissolved oxygen, dissolved salts, dissolved toxics and other contaminants, floating or suspended matter, pH, odor, opacity, temperature profiles, and other indicators.

3. **Soil Condition** as revealed by soil chemistry; erodibility; permeability; organic content; soil stability; physical composition, including particle sizes and microfauna; and other factors.

4. **Geological Condition** as indicated by surface and subsurface rock and other strata, including aquifers.

5. **Topography** as indicated by surface contours; the relief (elevations and gradients) and configuration of site surface features; and project size and location in the watershed, including position relative to similar or interdependent ecosystems.

6. **Morphology** as indicated by the shape and form of the ecosystem, including subsurface features. For a lake or reservoir, morphology includes shoreline circumference-to-area ratio, mean depth, and mean-depth-to-maximum-depth ratio. For rivers and streams, it includes channel planform and geometry. For wetlands, morphology includes inlets and outlets, channels, islands, adjacent uplands-to-wetlands ratio, fetch and exposure, and vegetation-water interspersion.

7. **Flora and fauna**, including density, diversity, growth rates, longevity, species integrity (presence of full complement of indigenous species found on the site prior to disturbance), productivity, stability, reproductive vigor, size-and age-class distribution, impacts on endangered species, incidence of disease, genetic defects, genetic dilution, elevated body burdens of toxic substances, and evidence of biotic stress.

8. **Carrying capacity, food web support, and nutrient availability** as determined for specific indicator species. Ultimately, these will be a function of nutrient availability in conjunction with other site-specific factors. Nutrient availability and nutrient flux patterns are therefore subsumed under "carrying capacity." However, an understanding of nutrient dynamics will give the resource manager more predictive capability than simply knowing current carrying capacity. Two questions of interest are whether the ecosystem is gaining or

losing nutrients, and whether the nutrient flux is comparable to that in the antecedent system.

Functional Characteristics

A fundamental function of rivers is the transport of water and sediments, and most of the physical, biological, chemical and sociological functions are derived from these basic functions. The transport of water and sediment are, in turn, influenced by the interaction of geologic, climatic, hydrologic, geomorphic, pedogenic (soil), and biotic processes. So many of the functions performed by streams are interrelated.

Alluvial riparian zones function as shallow aquifers that affect stream flows and create moist soil conditions favorable to riparian plant growth. Riparian vegetation contributes to the stream's geomorphic and hydrologic functions and helps establish the basic components of biological habitat, both aquatic and terrestrial. Riparian communities buffer the stream from upland stresses and are extremely important in regulating the stream's water quality.

Restoration practice is generally lacking in objectivity and the establishment of a functional basis for stream evaluations and restoration designs has obvious benefits. To date, nobody has proposed an acceptable list of stream and riparian functions, however. Considering the above information, stream and riparian functions can be grouped by ecosystem component (physical, chemical, biological and sociological), and might include a variety of processes related to:

- Surface and ground water storage, recharge, and supply
- Sedimentation
- Water quality maintenance
- Biomass production, food web support, and species maintenance
- Provision of shelter and food for ecosystem users
- Energy flow

Because of the complex interrelationships among these functions, it is often difficult to perform either a quantitative or qualitative analysis of the effects of various management measures. Considerable data and sophisticated analytical procedures are not uncommon. In completely evaluating a restoration project, one is in effect evaluating an entire ecosystem. A broadly representative range of assessment criteria must be used to reflect the major dimensions of the ecosystem, including its complex food webs, habitat heterogeneity, and dynamic physical, chemical, and biological processes. Thorough evaluation may become a complex, multidisciplinary process involving a great deal of data collection and necessitating that the resulting body of basically incomparable or unrelated data be reduced to manageable terms by using multi-attribute decision techniques.

An alternative to submerging the decision-maker in a sea of data is to strategically select assessment criteria that are indicators of other complex desired ecological states. For example, use of a measure such as the biomass of key indicator species may provide a great deal of information about the extent to which a particular function is being performed. Indicators should include both biotic and abiotic attributes of the ecosystem, and should be based on known relationships to ecosystem functions. These functions should be identified before the assessment takes place and should be linked to specific project objectives. Measurements of indicators should take into account both temporal variation and spatial heterogeneity.

Though a comprehensive listing of stream and riparian functions has not yet been established, the principal author of this handbook constructed a preliminary list of functions, indicators and their measures. These were organized, as described above, into the general categories of physical, chemical and biological, and are presented in Tables 3.1 through 3.4. These tables are intended merely to serve as the starting point for a restoration team interested in using a functional basis for the evaluation of a system.

There is considerable debate over the inclusion of sociological factors in the characterization of ecosystems. The same argument applies to the formulation of stream and riparian functions. On the one hand, humans are an important part of the ecology of most stream and riparian systems and may be one of the principal users. On the other hand, establishing social functions without introducing bias from “values” is difficult. Even seemingly straight-forward functions such as water supply, flood control, recreation, and navigation present these difficulties. The authors have elected to exclude social functions from the tables.

Ecological Relations

The stream corridor, watershed, and landscape are a complex of working ecosystems that influence and are influenced by neighboring ecosystems. Restoration and management success increases with an understanding of these relationships. Stream or corridor-specific design solutions may not resolve the problems and opportunities of the watershed or larger landscape. However, they can and should work with the larger systems of which they are a part. This approach promotes the adoption of the following principle objectives that should be included not only for specific projects but also in a broader management plan:

- Sustainable land uses
- Restored and protected streams and associated ecosystems
- Improved natural resource quality and quantity
- A diversity of native plants and animals
- A gene pool which promotes hardiness, disease resistance and adaptability
- A sense of stewardship
- Management measures that avoid narrowly focused and fragmented land treatment.

Table 3.1 Physical functions (hydrologic and hydraulic processes), indicators and measures

Function	***What is it and what does it do?***	***Indicators***	***Measures***
Short term surface water storage	Provides temporary water storage in the active channel and in the riparian area during floods, seasonal high water. Regulates discharge and replenishes soil moisture.	Presence of floodplain and/or channel constrictions. Riparian wetlands and depressions.	Simple backwater computations. Hydrologic routing models. Stream entrenchment. Watershed conditions such as % impervious surface.
Long term surface water storage	Provide habitat for water dependent species. Provide low velocity, low oxygen environment. Maintain base flow, seasonal flow and soil moisture.	Presence of perennial floodplain topographic features such as floodplain lakes, ponds, wetlands, and sloughs. Measure stream entrenchment; compare with Water Surface Elevation.	Topographic surveys. Gage records. Hydrologic models.
Surface / subsurface water connections	Movement of open channel flow to subsurface soils during times of high flows, or movement groundwater to the stream in times of drought. Exchange of chemicals, nutrients and water. Low flow augmentation and minor attenuation of high flows. Maintain habitat connectivity.	Invertebrates found in the hyporheic zone under floodplains. Presence of floodplain topographic features that connect the channel to groundwater recharge areas. Free-draining soils. Occurrence of flows sufficient to allow connectivity.	Groundwater levels. Stream baseflow. Hyporheic macroinvertebrate density. Complexity of microtopography.
Subsurface Storage of Water	Capacity of the subsurface riparian corridor to store groundwater for duration's of time. Maintains base flow, seasonal flow and soil moisture.	Moist soil conditions, hydrophytic vegetation. Adjacent wetlands. Groundwater elevation fluctuations.	Flux in groundwater elevations. Isotope dating. Watershed conditions such as % impervious surface. Texture, structure, and moisture of adjacent soils.
Energy Processes	The ability of a stream to convert energy between its potential and kinetic forms through changes in physical features, hydraulic characteristics, and sediment transport processes. Provides complexity of habitat, generates heat, reoxygenates flows. Energy gradient influenced by human land and water resource management activities.	Changes in physical stream features such as width, depth, slope bed and/or bank roughness. Changes in flow conditions. Erosion/deposition pattern change. Entrainment of sediments.	Determine Energy Grade Line and Hydraulic Grade Line and compare using simple computations or models at different flows. Quantify changes in physical stream feature or hydraulic features down at the channel and compare to reference channels.

Table 3.2 Physical functions (sedimentation processes, habitat & temperature), indicators and measures

Functions	*What is it and what does it do?*	*Indicators*	*Measures*
Maintain sedimentation processes	Sedimentation includes the erosion, transport, deposition and consolidation of sediments, as well as sediment sorting, armoring and other related processes. These processes are critical to the establishment of both aquatic and riparian habitat, and are an important part of nutrient cycling and water quality control.	Bed sediment character. Evidence of recent channel or floodplain sediment deposits and bed or bank erosion. Channel planform, section or grade changes. Active bars. Pioneer vegetation species. Changes in supply patterns, erosion patterns, and deposition patterns.	Bed material sediment loads and gradations. Stability Assessment techniques. Temporal changes in channel geometry. Watershed landuse and landuse changes. Sediment yield modeling. Sediment transport modelling. Composition and diversity of macroinvertebrates.
Maintain stream evolution	Streams evolve through a succession of forms. This evolution process is necessary to maintain appropriate energy levels in the system. It also promotes a level of dynamic activity necessary to maintain the ecological requirements of diversity and succession.	Systemic changes to channel cross section, planform or grade. Magnitude, frequency, and duration of flow changes. Bed armoring or sorting. Evidence of bed erosion or deposition. Bank erosion.	Stability Assessment techniques that quantify bed and bank stability. Channel Evolution Model stage. Rates of change of channel geometry parameters. Changes in the composition of the aquatic community.
Provision of habitat structure & substrate	Stream features (including riparian corridor) such as physical, hydrologic and hydraulic features to provide habitat architecture.	Presence, composition, frequency, and distribution patterns of physical characteristics such as pools, riffles, bedforms, specific depths and velocities, cover and substrate features, riparian corridor widths, etc., that are deemed important for the biotic community.	Aquatic & Riparian Habitat Assessment methods such as PHABSIM, RCHARC, RBPS, HEP, IBIs. Abundance and diversity of biota. Distribution and frequency of key physical parameters.
Maintain temperature	Ability of the riparian corridor to maintain temperatures sufficient to sustain the existing aquatic biotic community and to provide terrestrial microclimates preferred by riparian organisms.	Presence of a woody riparian community. **Presence of temperature intolerant biota.** **High dissolved oxygen.**	Periodic or continuous temperature recording over time. Fish, amphibian, avian and invertebrate species composition. Riparian Habitat quality assessment. Canopy closure.

Table 3.3 Chemical functions, indicators, and measures.

FUNCTIONS	What is it and what does it do?	Indicators	Measures
Maintain water quality: ***Maintain dissolved oxygen*** ***Buffer pH*** ***Regulate sediment transport*** ***Maintain conductivity*** ***Control pathogens/ viruses*** ***Remove and transform pollution*** ***Regulate metals cycles*** ***Remove and transport geochemical weathering products*** ***Maintain nutrient Cycles*** ***Carbon*** ***Nitrogen*** ***Phosphorus***	Ability of the stream to maintain water quality parameters necessary to support a potentially healthy biologic community. Riparian communities trap, retain and remove particulate and dissolved constituents of surface and overland flow that affect a stream's water quality.	Values of key water quality parameters. Presence and abundance of key biota that are indicators of a particular water quality parameter. Presence/absence of eutrophic indicators. Watershed conditions and landuse. Stream order.	Basic water quality parameters such as DO, pH, conductivity, turbidity, and temperature and their changes over time. Fish and invertebrate species composition, density and diversity. Measured changes in periphyton biomass through visual inspection or sampling Species composition and vigor of plant communities. Percentage of a watershed composed of specific landuses such as urban, agricultural, or mining.

Table 3.4 Biological functions, indicators, and measures.

FUNCTIONS	What is it and what does it do?	Indicators	Measures
Provides Habitat to: ***Level 1: food, air, water, shelter needs met*** ***Level 2: reproductive needs met*** ***Level 3: thriving needs met; safety, migration, overwintering, community population support***	Ability of the stream to produce habitat requirements to sustain health of well-balanced aquatic and riparian communities.	Composition, structure, extent, variability, diversity, abundance of habitat to provide these levels. Presence/absence of key indicator species.	Measures from Rapid Stream Assessment Procedure, or other habitat modeling such as RCHARC, PHABSIM, HEP. Comparison of biotic counts to reference IBIs
Produce biomass-detrital yield, microbial, periphyton, invertebrate, vertebrate, and vegetation growth.	Streams ability to promote organism growth.	Presence and abundance of indicator species. Presence and abundance of detrital material. Evidence of detrital shredding and decomposition.	Measure of detritus production. Biomass production of stream dependant species Measure of large woody debris frequency and density Measure of primary productivity
Maintain successional transitions	Streams ability to provide dynamic areas (such as where lateral stream migration is occurring) that promote vegetative succession. Benefits genetic variability and species diversity of vegetation.	Presence of a variety of different species and ages of vegetation adjacent to the stream. Active meander bends and point bar formations. Presence of pioneer species.	Quantity, densities, ages, and types of different vegetation. Rates of lateral stream migration. Abundance and distribution of pioneer species.
Maintain trophic complexity ***Autotrophs (plants): producers*** ***Heterotrophs-consumers/ decomposers***	Ability of the stream to maintain an optimal balance between primary producers and consumers to provide for a potentially healthy, diverse biologic community.	Evidence of detrital shredding and decomposition. Presence of invertebrate consumers. Periphyton growth on substrate.	Aquatic and riparian vegetation density. Periphyton biovolume. Density, composition and biomass of invertebrate consumers.
Supply nutrient ***Carbon export*** ***Nitrogen*** ***Phosphorus***	Ability of the stream to provide nutrients and maintain a biologic community capable of utilizing nutrients for nutrient cycling.	Presence of a balance of a variety of nutrients and aquatic and riparian organisms able to convert carbon, nitrogen and/or phosphorus from one form to another.	Measure of N:P ratios in water Diversity and composition of stream biota. Biomass of coarse and fine particulate organic material

Ecological Characterization

Diversity

One of the most often cited ecological objectives for stream restoration or management projects is the enhancement of diversity. The biological diversity and species abundance in streams depend on the diversity of available habitats. Naturally functioning, stable stream systems promote the diversity and availability of habitats. But the quantitative assessment of diversity at the ecosystem, habitat or community level remains problematic. While it is possible to define what is in principle meant by genetic and species diversity, and to produce various measures thereof, there is no unique definition and classification of ecosystems at the global level, and it is thus difficult in practice to assess ecosystem diversity other than on a local or regional basis and then only largely in terms of vegetation. Ecosystems further differ from genes and species in that they explicitly include abiotic components, being partly determined by soil parent material and climate.

Ecosystem diversity is often evaluated through measures of the diversity of the component species. This may involve assessment of the relative abundance of different species as well as consideration of the types of species. In the first instance, the more equally abundant different species are, then in general the more diverse that area or habitat is considered to be. In the second instance, weight is given to the numbers of species in different size classes, at different trophic levels, or in different taxonomic groups. Thus a hypothetical ecosystem which consisted only of several species of plants, would be less diverse than one with the same number of species but which included animal herbivores and predators. As different weightings can be given to these different factors when estimating the diversity of particular areas, there is no one authoritative index for measuring diversity. This obviously has important implications for the ranking of different areas.

Different measures of diversity can be applied at various levels of complexity, to different taxonomic groups, and at distinct spatial scales. Several factors should be considered in using diversity as a measure of system condition for stream corridor restoration. Principle among these are the level of complexity, the species of concern, and the scale.

Diversity can be measured at several levels of complexity—genetic, population/species, community/ecosystem, landscape and global. There is no single correct level of complexity to use, but most stream restoration projects support measures at the population/species or community/ecosystem level. The level of complexity chosen for a specific stream corridor restoration project should be determined based on careful consideration of the biological objectives of the project.

Overall diversity within any given level of complexity may be of less concern than diversity of a particular subset of species or habitats. This is particularly true when dealing with threatened or endangered species or designated critical habitats. Any important subsets of diversity should be identified when setting proect objectives.

Diversity can be measured within the bounds of a single community, across community boundaries, or in large areas encompassing many communities. Scalar diversity can be temporal as well as spatial. When establishing project objectives and discussing diversity, it is important that the restoration team address these issues of scale.

Measures of Diversity

Richness, abundance, and indices based on proportional abundance are the three main categories of diversity measures. Richness indices are measures of the number of species in a specific sampling unit and are the most widely used indices. Abundance accounts for the equitability of distribution of species. Indices based on the proportional abundance of species combine both richness and equitability into a single index. A variety of such indices exist, the most common of which is the Shannon diversity index:

$$H = -\Sigma p_i \ln (p_i)$$

where
H = index of species diversity
p_i = proportion of total sample belonging to the ith species

At the species level, a simple measure of richness is most often used in conservation biology studies. The many rare species that characterize most systems are generally of greater interest than the common species that dominate in diversity indices and accurate population density estimates are often not available. Simple measures of species richness, however, are not sensitive to the actual species composition of an area. Similar richness values in two different areas may represent very different sets of species. The usefulness of these measures can be increased by considering specific subsets of species of most concern, or by combining measures of species and habitat diversity with some measure of local rarity.

Instream Habitat

Instream habitats are the places where individuals, populations, or assemblages of fishes and other organisms can find the physical and chemical features needed for life. Habitat features include water quality, spawning sites, feeding areas, and migration routes. Habitat quality affects abundance and health of aquatic organisms as well as the species composition. In some cases, direct measures of biotic conditions can be used to evaluate or infer habitat character and value.

Much of the spatial and temporal variability of stream biota reflects variations in both abiotic and biotic factors, including water quality, temperature, streamflow and flow velocity, substrate, the availability of food and nutrients, and predator-prey relationships. These factors influence the growth, survival, and reproduction of aquatic organisms.

A number of measurement techniques and models are used to assess the physical character of instream habitats as they relate to aquatic organisms. Many that are based upon fishery resources are listed in Table 3.6. These techniques utilize a variety of habitat features as indices of fishery health. Similar approaches are used to evaluate invetrebrate habitat. The major stream habitat types that are colonized by epifaunal macroinvertebrates and generally support the highest quality diversity in stream ecosystems are described below.

Table 3.6 Methods used by federal government fishery agencies for habitat assessment and analysis (codes listed below).

Agency	*Full method*	*Abbreviated method*
US Geological Survey	GS-NAWQA	.
US Environmental Protection Agency	EPA/EMAP-L, EPA/EMAP-S, EPA-RBP	.
US Fish and Wildlife Service	FWS-HEP	FWS-AHC
Army Corps of Engineers	FWS-HEP, WY	COE-AHAG, COE-MI
Forest Service, Northern Region	FS-HR	.
Forest Service, Rocky Mtn. Region	FS-RM	.
Forest Service, Southwestern Region	FS-HR, FS-GAWS	.
Forest Service, Intermountain Region	FS-HR, FS-GAWS, FS-IM	.
Forest Service, Pacific Southwest Region	.	FS-GAWS
Forest Service, Eastern Region	FS-HR	.
Forest Service, Alaska Region	FS-AK	.
Forest Service, ECOMAP Group	FS-HF	.
National Biological Service	IFIM	.

Acronym	*Full Name*
COE-AHAG	*Aquatic Habitat Appraisal Guide*
COE-MI	*Lower Mississippi River Habitats*
EPA/EMAP-L	*EMAP Lakes*
EPA/EMAP-S	*EMAP Wadeable Streams.*
EPA-RBP	*Rapid Bioassessment Protocols*
FS-AK	*Stream Survey Protocol*
FS-GAWS	*General Aquatic Wildlife System*
FS-HF	*Aquatic Hierarchical Framework*
FS-HR	*Basinwide Visual Estimation Technique*
FS-IM	*Evaluating Stream, Riparian, & Biotic Conditions*
FS-RM	*Stream Channel Sites*
FWS-AHC	*Aquatic Habitat Classification System*
FWS-HEP	*Habitat Evaluation Procedure*
GS-NAWQA	*NAWQA Stream Habitat Component*
IFIM	*Instream Flow Incremental Methodology*

Flow Condition

The spatial and temporal characteristics of streamflow, such as fast versus slow, deep versus shallow, turbulent versus smooth, and flooding versus low flows, are can affect both micro- and macro-distribution patterns of numerous stream. Many organisms are sensitive to velocity because it represents an important mechanism for delivering food and nutrients yet also may limit the ability of organisms to remain with a stream segment. Some organisms also respond to temporal variations in flow, which can change the physical structure of the stream channel, as well as increase mortality, modify available resources, and disrupt interactions among.

Extreme low flows may limit young fish production because such flows often occur during periods of recruitment and growth. Extreme high flows can mobilize significant amounts of bed material and dislocate a large fraction of the invertebrate community in a stream reach. High flows are also cues for timing migration and spawning of some fishes. The velocity in streams determines the vegetation forms that can develop and sustain themselves.

Riffles and pools (and runs) are common features throughout most mountain and piedmont streams. Riffle/pool streams provide a great diversity of velocity conditions and, in turn, are most apt to support a diverse faunal community. In many high-gradient streams, riffles will be dominant. However, riffles are not a common feature of most coastal or other low-gradient streams.

Cover

Instream cover, usually in the form of boulders or large woody debris, can provide habitat for invertebrates, velocity refuges, hiding places from predators, and attachment sites for adhesive fish eggs. Because depth and velocity of flow are closely related to certain types of cover features, maximizing cover often increases diversity in depth and velocity. Instream cover is an important component of most lotic habitats and generally, more instream cover means better fish habitat.

Riparian vegetation is also an important cover feature because of its ability to attenuate light and temperature in streams. Direct sunlight can significantly warm streams, particularly during summer periods of low flow. A lack of cover also affects stream temperature during the winter. Sweeney (1993) found that while average daily temperatures were higher in a second-order meadow stream than in a comparable wooded reach from April through October, the reverse was true from November through March. Temperature differences of 2-6 °C can be biologically significant and may alter key life-history characteristics of aquatic species.

Substrate

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes.

Stream biota respond to the many abiotic and biotic variables influenced by substrate. As a general rule, substrate size decreases with increasing stream order, with substrate in the largest rivers usually consisting of sand, silt, and clays. Many fishes, including some culturally and economically important species, cannot reproduce successfully unless gravel or larger substrate is available. Thus, gravel and larger substrates are often very important habitat components.

Differences in species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach. This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams. Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms. In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris (LWD) that falls into the stream can be the most important substrate.

Stream substrates constitute the interface between water and the hyporheic zone of the aquatic system. The hyphorheic zone is the area of free exchange between surface and ground water. On small streams, the hyphorheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock and are generally not continuous. On mid-order channels with more extensive floodplains, the spatial connectivity of the hyphorheic zone increases. The hyphorheic zone is usually largest on high-order streams, but tends to be discontinuous because of features such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems.

Primary Productivity and Organic Material

The role of primary productivity of streams can vary depending on geographic location, stream size, and season. Primary productivity is of less importance in shaded headwater streams than in larger streams where riparian vegetation no longer limits the entry of light to stream periphyton. The loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as eutrophication. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures. Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

In many streams, shading or turbidity limit the light available for algal growth, and biota depend highly on allochthonous organic matter, such as leaves and twigs produced in the surrounding watershed. Once leaves or other allochthonous materials enter the stream, they undergo rapid changes. Soluble organic compounds, such as sugars, are removed via leaching. Bacteria and fungi subsequently colonize the leaf materials and metabolize them as a source of carbon. The presence of the microbial biomass increases the protein content of the leaves, which ultimately represents a high quality food resource for shredding invertebrates.

Leaf decomposition occurs by a sequential combination of microbial decomposition, invertebrate shredding, and physical fractionation. Leaves and organic matter itself are generally low in protein value. However, the colonization of organic matter by bacteria and fungi increases the net content of nitrogen and phosphorus due to the accumulation of proteins and lipids contained in microbial biomass. These compounds are a major nutritive source for aquatic invertebrates. The combination of microbial decomposition and invertebrate shredding/scraping reduces the average particle size of the organic matter, resulting in the loss of carbon both as respired $CO2$ and as smaller organic particles transported downstream. These finer particles, lost from one stream segment, become the energy inputs to the downstream portions of the stream. Decaying organic matter represents a major storage component for nutrients in streams, as well as a primary pathway of energy and nutrient transfer within the food web. Ultimately, the efficiency of retention and utilization is reflected at the top of the food web in the form of fish biomass.

Riparian and Floodplain Habitat

Aquatic river-edge ecotones provide outstanding ecological boundaries. The riverine littoral zone provides comparatively calm water and stable sediments, with habitat structure provided by rocks, snags, plants, and bank irregularities. The littoral boundary is a key part of the riparian corridor, being a zone of concentrated physical and biological diversity and a resource for both riverine and terrestrial communities.

The riverine littoral zone is characterized in most areas as the river bank, from the edge of the water to the top of the bank. This zone is unique because it provides constant contact between the aquatic and terrestrial portions of the riparian corridor. It is directly affected by the hydrologic and hydraulic character of the river. High river stages inundate the entire littoral zone and provide access to the upper littoral zone resources by fish and other aquatic or amphibious species. Low river stages remove access to refuge, food, and spawning areas for aquatic and amphibian animals as the higher elevation areas become exposed.

Overhanging vegetation in this zone shades and cools the water and surroundings, helping to provide thermal refuges. Roots and debris are colonization sites and food sources for macroinvertebrates and provide refuge from predators and currents among the roots, rocks, and other structures. Vegetation in this zone stabilizes streambanks and improves water quality. Stable banks provide nesting sites for a variety of vertebrate species. Several elements of fish habitat, including temperature, cover, and food are influenced by the riparian zone.

Backwater areas are an important component of the riparian zone. Longevity, productivity, and habitat quality of backwaters are greatly affected by the amount of protection from main river channel flooding and sedimentation, number and type of connections to the river, flushing rate, and degree of water-level fluctuation. Direct openings to the river permit water exchange that can prevent stagnation and oxygen depletion, renew organic material and nutrients, and allow export of materials such as detritus, plankton, and aquatic invertebrates to the river. Fish are known to readily enter backwaters, especially for spawning, and the free movement of fish into and out of these areas in response to changing conditions is important for maintaining healthy populations. However, if there are numerous uncontrolled connections to the main channel, then high rates of water movement throughout the backwater will flush out nutrients and preclude development of slow-water habitat features.

Riparian vegetative communities are a valuable source of energy for the biological communities, provide physical habitat, and moderate solar energy fluxes to and from the surrounding aquatic and terrestrial ecosystems. The vegetative community grows in an annual cycle of active growth/production, senescence, and relative dormancy. The growth period is characterized by the photosynthetic process, through which inorganic carbon is converted to organic plant materials. A portion of this organic material is stored as above- and below-ground biomass, while the remainder is lost to the stream or to the soil in the form of leaves, twigs, and decaying roots. This organic fraction, rich in biological activity of microbial flora and microfauna, represents a major storage and cycling pool of available carbon, nitrogen, phosphorus, and other nutrients. Some of this material, particularly the LWD, provides important cover and substrate for aquatic organisms.

The characteristics of the vegetative communities directly influence the diversity and integrity of the faunal communities. Vegetative communities that cover a large area and that are diverse in their vertical and horizontal structural characteristics can support far more diverse faunal communities than relatively homogenous vegetative communities.

The quantity of terrestrial vegetation, as well as its species composition, can directly affect stream channel characteristics. Root systems in the stream bank can bind bank sediments and moderate erosion processes. Trees and smaller woody debris that fall into the stream can deflect flows and induce erosion at some points and deposition at others. Thus woody debris accumulation can influence pool distribution, organic matter and nutrient retention, and the formation of microhabitats that are important fish and invertebrate aquatic communities.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishing corridors that are structurally different from native systems or that are inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and, where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages (Knopf et al. 1988, Knopf 1992).

Water Quality

The three most important and arguably the three easiest to measure water quality parameters are temperature, dissolved oxygen and pH. Their significance is discussed below and is followed by a discussion of the importance of riparian systems in maintaining good water quality.

Water Temperature

Temperature governs many biochemical and physiological processes in aquatic organisms. The relationships between temperature and growth, development, and behavior can be strong enough to affect geographic ranges of some species. Water temperature is one of the most important factors determining the distribution of fish in freshwater streams, due both to direct impacts and influence on dissolved oxygen concentrations, and is influenced by local conditions, such as shade, depth and current. Many fish species can tolerate only a limited temperature range for certain life stages. Table 3.7 presents temperature requirements for several fish species.

Dissolved Oxygen

Dissolved oxygen at appropriate concentrations is essential not only to keep aquatic organisms alive, but also to sustain their reproduction, vigor, and development. Oxygen enters the water by absorption directly from the atmosphere and by plant photosynthesis. Streams generally contain an abundant dissolved oxygen supply, so most stream fauna have a narrow oxygen tolerance and are sensitive to low dissolved oxygen levels.

Fish die by suffocation when the demand for oxygen by biological and chemical processes exceeds the oxygen input by reaeration and photosynthesis. Conditions of low oxygen are usually associated with slow current, high temperature, extensive growth of rooted aquatic plants, algal blooms, or high concentrations of organic matter. But stream communities are also susceptible to pollution that reduces the dissolved oxygen supply.

Table 3.7 Temperature requirements and preferences for select fish species.

Species, Life Stage	Upper Limit(°C)[1]	Optimum Range(°C)[1]
Coho salmon	25.5	4.0 - 14.0
juvenile	25.0	4.4 - 9.4
spawning	25.8	6.0 - 12.0
egg protection	n/a[2]	4.4 - 13.3
Chinook salmon		
spawning	16	5.6 - 10.6
egg protection	16	5.0 - 14.4
Sockeye & kokanee salmon	22	5 - 17
juvenile	18	11-15
spawning	10	n/a
egg protection	13	n/a
Chum salmon	n/a	8.3 - 15.6
juvenile	23.8	12.0 - 14.0
spawning	n/a	7.2 - 12.8
egg protection	n/a	4.4 - 14.0
Pink salmon	25.8	5.6 - 14.6
juvenile	n/a	n/a
spawning	n/a	7.2 - 12.8
egg protection	n/a	4.4 - 13.3
Atlantic salmon	n/a	n/a
spawning	n/a	5.0
egg protection	12.0	6.0
Cutthroat trout	22.0	9 - 12
spawning	n/a	6 - 17
eggs	n/a	10 - 11
juveniles	21	11 - 21
Rainbow trout & steelhead	25	12 - 18
spawning	n/a	10 - 15.5
Brook trout	24	11 - 16
spawning	n/a	4.5 - 10
Brown trout	27	12 - 19
spawning	27	2 - 13
juvenile	27	7 - 19
Lake trout	23.5	4 - 18
spawning	n/a	4.5 - 14
Smallmouth bass	32	21 - 27
spawning	n/a	12.8 - 21
Spotted bass	34	24
spawning	n/a	18 - 21
Largemouth bass	36	24 - 30
spawning	30	21
Black crappie	27	19 - 24
spawning	18	15 - 18
White crappie	28	20 - 25
spawning	18	18 - 20
Bluegill	32	n/a
spawning	25	21 - 23
Anadromous striped bass	27	16 - 25
spawning	n/a	17 - 19
White Bass	n/a	19 - 28
spawning	n/a	15.5 - 16.7
Northern pike (summer)	28	n/a
Spawning	11	n/a
Channel catfish (summer)	32	n/a
spawning	27	21 - 29
Longnose sucker	n/a	10 - 15
spawning	n/a	10 - 15
Carp (spawning)	21	16 - 20
Emerald shiner	30	n/a
spawning	24	n/a

[1]Unless indicated, limits and ranges are for adults (migrating adults for anadromous salmonids).
[2]n/a - not available

pH

Aquatic organisms generally exist and thrive in aquatic systems with nearly neutral hydrogen ion activity (or a pH of about 6-8). Deviations, either toward a more basic or acidic environment, increase chronic stress levels and eventually decrease species diversity and abundance. One of the more widely recognized impacts of changes in pH has been attributed to increased acidity of rainfall in some parts of the United States, especially areas downwind of industrial and urban emissions. Of particular concern are environments that have a reduced capacity to neutralize acid inputs because soils have a limited buffering capacity.

Riparian Considerations

Riparian vegetation plays a vital role in the water quality functions of riverine systems. Due to their landscape position, riparian areas intercept overland and ground water flow from adjacent uplands as well as overbank flow from rivers. They are buffers where materials and energy from a broad areas and diffuse sources converge. Floodplains control large exchanges of sediments, organic matter, and nutrients among these ecosystems.

The quality of water flowing through riparian areas is changed by the contact with soils and vegetation. There is a flux of material that often results in improved water quality, but the pathways along which materials move in riparian ecosystems are complex and highly interrelated and thus difficult to quantify.

Water quality functions performed in riparian ecosystems are dominated by particulate removal because the hydrology is dominated by surface flow and erosion is a natural source of particulates. Riparian corridors differ in their particle retention effectiveness, depending largely on roughness and the capability to trap materials. Plant stems, woody debris, root mounds from fallen trees, and leaf litter are the primary features the contribute to ground surface roughness in riparian areas. Vegetative cover in riparian areas reduces sediment inputs into streams by reducing potential soil erosion. As organic and mineral sediments are trapped, a great deal of dissolved materials in surface water can also be removed from the water column by adsorption to the particles. In addition to trapping sediments, plants also reduce concentrations of dissolved materials in surface and subsurface water by taking up nutrients and incorporating them into plant matter.

Nutrient Dynamics

Dissolved materials such as nutrients and metals are removed from surface and subsurface water by several mechanisms. The most effective removal mechanism, particularly for phosphorus, is adsorption to mineral and organic particulates. The particles fall out of suspension and become buried, removing the materials from further cycling. Some nutrients such as nitrogen are lost to the atmoshpere as gases released from anaerobic microbial processes in wetlands. Plants contribute to these mechanisms and also take up nutrients that become incorporated into leaves, stems, and roots.

Flora and Fauna

The ecological integrity of stream corridor ecosystems is directly related to the integrity and ecological characteristics of the vegetative communities that make up and surround the corridor. These vegetative communities are a valuable source of energy for the biological communities, provide physical habitat, and moderate solar energy fluxes to and from the surrounding aquatic and terrestrial ecosystems. The sensitivity of animal communities to vegetative characteristics is well recognized. Numerous animal species are associated with particular plant communities, many require particular developmental stages of those communities (e.g., old-growth), and some depend on particular habitat elements within those communities (e.g., snags). The structure of streamside plant communities also directly affects aquatic organisms by providing inputs of appropriate organic materials to the aquatic food web, by shading the water surface and providing cover along banks, and by influencing instream habitat structure through inputs of woody debris.

Stream corridors are used by wildlife more than any other habitat type and are a major source of water to wildlife populations, especially large mammals. Stream corridors play a large role in maintaining biodiversity for all groups of vertebrates. High foliage density and diversity in the vertical and horizontal dimension are among the variables most frequently associated with high avian densities and diversities in riparian zones, and the food and cover offered by riparian vegetation is extremely important to terrestrial animals. Riparian ecosystems are also important wildlife migration corridors. The riparian zone influences several elements of fish habitat, including temperature, cover, and food. Loss of vegetative cover and undercut banks can decrease the amount of suitable habitat, thereby reducing stream productivity and fish carrying capacity. Streambank vegetation also can be an important source of fish food. Small fish use slower water along margins of larger streams and depend on terrestrial organisms from streamside vegetation for food because most aquatic drift organisms escape them.

The faunal composition of a stream corridor is a function of the interaction of food, water, cover, and spatial arrangement. These habitat components interact in multiple ways to provide eight habitat features of stream corridors:

- Presence of permanent water sources.
- High primary productivity and biomass.
- Dramatic spatial and temporal contrasts in cover types and food availability.
- Critical microclimates.
- Horizontal and vertical habitat diversity.
- Maximized edge effect.
- Effective seasonal migration routes.
- High connectivity between vegetated patches.

Metrics used for biological condition assessments of habitat include taxa richness, composition, tolerance, and trophic dynamics.

Taxa richness, or the number of distinct taxa, represents the diversity within a sample. Taxa richness is a key metric in a multimetric indices as well as for fish, benthos, and in the EPA's RBP's. Taxa richness usually consists of species level identifications but can also be evaluated as designated groupings of taxa, often as higher taxonomic groups (i.e., genera, families, orders, etc.) in assessment of assemblages. Increasing diversity correlates with increasing health of the assemblage and suggests that niche space, habitat, and food source are adequate to support survival and propagation of many species. Number of taxa measures the overall variety of the assemblage.

Composition measures can be characterized by several classes of information. Identity is the knowledge of individual taxa and associated ecological patterns and environmental requirements. Key taxa (i.e., those that are of special interest or ecologically important) provide information that is important to the condition of the targeted assemblage. The presence of exotics or nuisance species may be an important aspect of biotic interactions that relates to both identity and sensitivity. Measures of composition provide information on the make-up of the assemblage and the relative contribution of the populations to the total fauna. Relative contribution of individuals to the total fauna - a reflection of interactive principles - is used rather than absolute abundance because a healthy and stable assemblage will be relatively consistent in is proportional representation, though individual abundance may vary in magnitude. Percentage of the dominant taxon is a simple measure of redundancy. A high level of redundancy is equated with the dominance of a pollution tolerant organism and a lowered diversity.

Tolerance/Intolerance measures are representative of relative sensitivity to perturbation and may include numbers of pollution-tolerant and -intolerant taxa or percent composition. Tolerance is generally non-specific to the type of stressor. However, some metrics such as the Hilsenhoff Biotic Index (HBI) (Hilsenhoff 1987, 1988) are oriented toward detection of organic pollution; the Biotic Condition Index (Winget and Mangum 1979) is useful for evaluating sedimentation. The Florida Index (Ross and Jones 1979) is a weighted sum of intolerant taxa (insects and crustaceans) found at a site. The tolerance/intolerance measures can be independent of taxonomy or can be specifically tailored to taxa that are associated with pollution or habitat degradation tolerances.

Trophic dynamics encompass functional feeding groups, and provide information on the balance of feeding strategies in the assemblage. Examples involve the feeding orientation of scrapers, shredders, gatherers, filterers, and predators. Trophic dynamics include the relative abundance of herbivores, carnivores, omnivores, and detritivores. Without relatively stable food dynamics, an imbalance in functional feeding groups will result and reflect stressed conditions. Trophic metrics are surrogates of complex processes such as trophic interaction, production, and food source availability. Specialized feeders, such as scrapers, piercers, and shredders, are the more sensitive organisms and are only represented in healthy streams. Generalists, such as collectors and filterers, have a broader range of acceptable food materials and thus are more tolerant to pollution that might alter availability of certain food.

The Roles of Vegetation

Vegetation can aid erosion control through five mechanisms: reinforce soil through roots; dampen waves or dissipate wave energy; intercept water; enhance water infiltration; and deplete soil water by uptake and transpiration. More discussion of the roles of vegetation is presented in Chapter 5, but one of the most critical yet least well studied aspects of riparian vegetation is the root system, discussed here.

Roots contribute to many functions of riparian vegetation. Hydrology of riparian areas is affected by the increased infiltration of water along root channels and the depth to which roots can access water. Substrate stability is increased by roots binding soil into aggregates, which are in turn broken up by the mechanical effects of the living roots and kept from coalescing into clods. Nutrients are transformed with oxygen transported into saturated soils via. Roots anchor vegetation in place. Below ground fauna use roots for food. Roots, however, are particularly difficult to access and study, so much of the information regarding roots is indirect or anecdotal. Of importance in riparian areas is an understanding of the depth, density, and strength of roots.

In general, the larger the plant, the larger the root system. Tree root systems extend out roughly 1.5 times the canopy diameter. Depth of the root system is highly dependent on species characteristics and site limitations. Some species, called phreatophytes, have very deep root systems that can reach deep ground water (see next section). Many species such as pine trees and members of the carrot family (Apiaceae) have taproots that extend straight down into the ground. Tap roots function for increased plant stability and acess of deep water and nutrients. It is the non-woody, fibrous roots, however, that are primarily responsible for uptake of most nutrients and water. All plants have fibrous roots. Most fibrous roots are generally located in the top 30 cm of soil and can become very dense and effectively bind upper soil layers. Trees and shrubs develop networks of woody roots that extend farther into the ground. This network of woody roots includes fibrous roots that in combination strongly bind soils into aggregates and provide sediment stabilization to much greater depths than fibrous roots alone. This is why trees and shrubs provide better shoreline stabilization in most cases than herbaceous species with relatively shallow roots.

Soils

Stream corridor functions depend soils and associated vegetation. When designing stream corridor restoration measures, it is important to carefully analyze soils data and their related potential and limitations to support diverse native plant and animal communities.

The functions of soil and the connection between soil quality and runoff and water quality need to be identified and considered in any stream corridor restoration plan and design. For all land uses, emphasis needs to be placed on implementing conservation land treatment that promotes soil quality and the ability of the soils to carry out four major functions:

- Regulating and partitioning the flow of water (a conduit and filter function)
- Storing and cycling nutrients and other chemicals (a sink and filter function)
- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials (a filter, sink, and barrier function)
- Supporting biological activity in the landscape (a source and habitat function)

Soils that have been in row crops or have undergone heavy equipment traffic (as with construction) may develop a relatively impermeable compacted layer (plow pan or hard pan) that restricts water movement and root penetration. Such soils may require deep plowing, ripping, or vegetative practices to break up the pan, although even this is sometimes ineffective. Deep plowing is usually expensive and, at least in the East, should only be used if the planting of a species that is able to penetrate the pan layer is not a viable option.

On new or disturbed substrates, or on row-cropped sites, essential soil microorganisms (particularly mycorrhizal fungi) may not exist. These are most effectively replaced by using rooted plant material that is inoculated or naturally infected with appropriate fungi, or by stockpiling and reincorporating local topsoils into the substrate prior to planting. Particular care should be taken to avoid disturbing existing large trees or stumps, as the soils around and under them are likely source areas for re-establishment of a wide variety of microorganisms appropriate to the site. Inoculation can be useful in restoring some soil mycorrhizal fungi for particular species when naturally infected plant stock is unavailable.

Soil salinity is another important consideration in restoration work because salt accumulation in the soil can restrict plant growth and negatively affect establishment of riparian species. High soil salinity is not common in healthy riparian ecosystems where annual spring floods remove excess salts. Additionally, soil salinity can be altered by leaching salts through the soil profile with irrigation. But because of agricultural drainage and altered flows due to dam construction, salt accumulation often contributes to the decline of riverside vegetation communities. Soil sampling throughout a project site may be necessary when salinity is a concern, since salinity can vary across a floodplain, even on relatively small sites of less than 20 acres. In areas where salinity is a problem, it is especially important to select planting materials adapted to the saline soil environment.

Soils and subsurface materials should be evaluated for the following soil attributes:

- proportions of sand, silt, clay
- gravel content
- organic material
- permeability
- drainage potential
- erodibility
- soil chemistry
- nutrients

When considering soil properties, it is important to distinguish between soil properties as they relate to the biological functioning of the wetland and soil properties as they affect the geotechnical function and design of the wetland. The term soil substrate could be used to refer to the medium that performs biological functions and the physical properties (geotechnical engineering aspects) of the soils as they apply to site selection and construction be referred to as subgrade elements of the wetland system. When analyzing the qualities of the soils on potential sites it is important to consider the different functions of soil. In addition, soil properties vary along elevational gradients and should be tested along any gradients in order to obtain complete results

Land Use

The structural and functional attributes of stream ecosystems are impacted by a range of human disturbances. Over half of the wetland and riparian zones have been destroyed in the coterminous 48 States, and researchers have estimated that 90 percent of southwest riparian systems have been destroyed. Because of their location in floodplains, destruction of riparian ecosystems is largely associated with man's activities, especially clearing for agriculture, stream-channel modifications, water impoundments, and urbanization. Narrower riparian areas are more easily altered and potentially degraded. Because riparian zones often follow the gradual elevational changes of a watershed, road and pipeline construction often impacts riparian ecosystems. Even recreational development can destroy natural plant diversity and structure, lead to soil compaction and erosion, and disturb wildlife.

Native riparian ecosystems, especially in the arid Southwest, are disappearing rapidly. About 1,200 ha/year of riparian vegetation are being removed along the lower Colorado River (Anderson et al. 1979). Many cottonwood (*Populus* spp.) communities of this area have been lost to expanding agriculture, livestock grazing, channelization projects, stream dewatering, inundation by reservoir construction, and groundwater depletion. Dams also have expedited the natural loss of riparian communities by stopping annual flooding. Cessation of annual floods and natural channel movements curtail the formation of the basic cottonwood seedling habitat--bare sandy soils with high water tables--which appears to be essential for seed germination. In addition, domestic livestock concentrate in riparian communities and heavily graze young cottonwoods.

Riparian areas are widely recognized as crucial to the overall ecological health of rangelands in the western U.S.; however, many are in degraded condition, largely as a result of poorly managed livestock grazing. Riparian areas represent only about 1percent of the more than 250 million acres of Federally owned rangeland. Riparian areas, however, have ecological importance far beyond their relatively small acreage because they have a greater quantity and diversity of plant species than adjoining land. Livestock tend to congregate in riparian areas for extended periods, eat much of the vegetation, and trample streambanks, often eliminating other benefits of riparian habitat (e.g., fish and wildlife habitat, erosion control, floodwater dissipation).

In the Pacific Northwest, stream corridors are major sources of erosion. Human activities such as logging, urban development, grazing, cropping, and recreational activity have increased surface runoff, removed protective riparian vegetation, and altered flows, often with catastrophic effects. About 10 million tons of sediment erode from streambanks each year in Oregon and Washington alone.

Mining activity, especially in the East, has destroyed many riparian habitats. For example, central Florida's phosphate district has been surface mined since 1908, and by 1975 over 60,000 acres (much of which was wetland) had been abandoned without reclamation (Clewell 1983). When reclamation of active mines became mandatory in 1975, most mine cuts were filled with overburden, sand tailings, and waste clays. Insufficient material remained to fill all mine cuts to the original grade of the land; thus, some cuts remained as relatively deep lakes, whereas others were filled and reclaimed as uplands. Reclamation of riparian and wetland habitats in Florida's phosphate district has been attempted only since 1978.

In the Southeast, over 90% of original bottomland forest has been converted to other land uses, primarily agriculture (Haynes and Moore 1988). Some major river systems also have had a long history of land alterations associated with flood control measures. Since the late 17th century, levees and borrow pits have been constructed along the lower Mississippi River. The 600 miles of the river between the Gulf of Mexico and Cape Girardeau, Missouri, is contained by over 2,000 miles of levees and has about 40,000 acres of borrow pits from which the levee material was taken (Landin 1985). As native riparian landscapes have been increasingly impacted by flood control projects, the need has grown for restorative mitigation, not only along existing rivers and streams but also on newly created floodways and distribution.

In urban communities one of the major problems facing local governments involves an economically and environmentally acceptable solution to increased flooding of urban streams. Flood correction and control typically includes stream channelization (i.e., widening, straightening, or deepening a stream channel). Channelization tends to adversely affect the physical and biological environment and to reduce the aesthetic quality of the stream.

One type of land use index is percentage of land use type (e.g., agricultural, residential/urban, forested) by area, or percentage change in area from one type to another between time periods. The intensity of the activity is also a vital land use characteristic. Where possible, pertinent information should be collected so that indices such as livestock density, septic system density, traffic density, or proportion of impervious surfaces, can be used to represent the particular dynamics of an area. These can then be related to the condition or change in water quality, which is represented by indicators.

Succession

The maturation process of natural plant communities is termed "succession" or community development. Plant communities develop from two starting conditions. The first type of development, often called primary succession, takes place on newly formed areas where no plant community as ever occurred before, such as on volcanic flows, that eventually support diverse, mature plant communities. In this situation, community development can be extremely slow. Soils must form. Colonization by microbes, plants, and animals is slow at first due to the extremely harsh and stressful conditions. Establishment of riparian plant communities on newly formed point bars can be considered to be primary succession.

Plant communities, however, more commonly develop following a disturbance that is severe enough that community development is set back to earlier developmental stages or the system must develop anew. This second type of development is called secondary succession. An example of secondary succession is the development of a forest over many years after an agricultural field is left fallow. In this situation, plant community development is more rapid. Soils capable of supporting plants are already formed. Site conditions are not as harsh and colonization is rapid; annual plant species are present in the first year. The types of plants and animals present will change over time. For example in classical old field succession, annual and grass species are often the first dominant plant species as a site develops. As colonizing plants become established, conditions for plant growth are improved and different species become dominant that are not tolerant of the harsher site conditions. Shrubs may dominate early and mid developmental stages. Trees begin to colonize a site during early succession, but do not dominate the site structurally until mid to late successional phases. Eventually, the rate of new species introductions decreases, the plants on site regenerate themselves, and the species composition stabilizes. At this point, the community is considered to be a in a "climax" or steady state. Many cases of riparian community succession can be considered secondary succession because site conditions retain some of the components of the degraded system after the disturbance.

Succession of riparian plant communities is integrally related with the associated stream dynamics. It is the sequence of floods and shifting sediments that create new surfaces and deliver seeds of colonizing species. Seeds of many riparian species such as maples and willow are carried by water and deposited on newly exposed areas. Animals deposit seeds from fruit they have eaten such as mulberry and elderberry (*Sambucus* spp). Colonizing plants may also result from clumps of plants that have broken off eroding areas and subsequently stranded on bars downstream.

There are relatively few plant species that are capable of becoming established on newly developed bars because the environmental conditions are often very harsh. With little organic matter or soil development, the exposed bars dry rapidly following falling river levels. Seeds and new seedlings are often desiccated and die before root systems are developed that can reach the groundwater. Annual floods inundate and destroy much of the existing vegetation. In addition, as the bars dry out, winds blow sands that may completely cover seedlings, uncover roots, or undermine plants and blow them away. The point bar colonizing species share several adaptations that ensure the establishment of floodplain forestes despite the vagaries of the river. These include an extended period of seed dispersal, large numbers of seeds, and plumes that carry the seed on the water and become entrapped in sands.

In spite of the harsh conditions, there is often a fairly dense cover of plants on newly deposited bars. Willow, cottonwood, and alders are the most common tree species that colonize newly developed bars in many kinds of streams. Cottonwood (*Populus deltoides*), sandbar willow (*Salix interior*), and salt cedar (*Tamarix gallica*) are common colonizers on bars of the southwest. Various willow, balsam popular, and mountain alder (*Alnus incana*) are the primary tree-colonizers in the northwest. Black willow is a primary colonizer of depositional bars of eastern rivers. In riparian communities of the arid southwest, the same species that colonize depositional bars ultimately constitute the mature community (Lowe 1964). Cottonwood (*Populus fremontii*), willow (*Salix bonplandiana, S. gooddingii*, and others), sycamore (*Platanus racemosa wrightii*), ash (*Fraxinus velutina*), and walnut (*Juglans microcarpa major*) are common species in climax riparian zones. See Appendix A for additional woody species that colonize in river and stream channels.

Grasses and herbs are often among the colonizing plants on depositional bars, but they tend to comprise a minor component of the total biomass that is dominated by woody species. Because they are not structurally resistant to the stress of flood flows, seedling herbs are often uprooted and washed away if flooded too soon after germination. Herbaceous species tend to become established, therefore, on higher or protected portions of depositional bars or following the establishment of shrubs. Alternatively, if depositional bars are adjacent to established herbaceous communities, existing plants may be able to spread vegetatively onto the new bars and rapidly establish robust vegetation. There are many desirable species capable of vegetative spread. However, common reed and cattails are examples of nuisance species with horizontal underground stems that readily spread vegetatively. These are very aggressive species that can become nuisances along many waterways due to their dense growth and minimal wildlife habitat value.

Once established, the vegetation on depositional bars provides resistance to flood waters, slowing the velocity and increasing further deposition. Elevation of the bar surface increases as sediments accumulate around stems. All plants contribute to the resistance but woody perennials are most important. Deposition amounts eventually decrease as the bar becomes inundated less frequently. Decreased periods of inundation and reduced current velocities over the bar result in improved conditions for establishment of additional species. Further increases in elevation with sedimentation and organic matter accumulation allow continued decreases in period and frequency of inundation and additional species to survive. Surviving willow trees in interior portions of the diverse bottomland hardwood forests of the Southeast are evidence of historic river movements.

The degree to which a plant community will develop and change over time since establishment on a river bar depends on the area and behavior of the river. The lack of succession from colonizing species in the arid Southwest forms one end of a continuum. Floods that destroy riparian forests recur on roughly 100 year cycles in the Southwest; this may be adequate to retard succession. While some newly colonized areas may be destroyed by floods, many are eventually abandoned by the river as it changes course. Although floods still occur in the abandoned areas, succession can proceed under less stressful conditions. Just as stable river channels have areas of erosion and deposition, stable riparian plant communities have areas of regeneration and loss. Ideally, as point bars are creating areas for colonization, eroding banks are removing equal areas of mature communities in a dynamic equilibrium.

Bio- and Habitat assessments

Preliminary Watershed Assessments

Much has been said about the need to use "holistic" perspectives that consider the entire watershed when contemplating stream restoration options. Unfortunately, political, programmatic and jurisdictional boundaries seldom correspond with watershed boundaries and restoration projects focus on specific sites. Without a comprehensive reach or watershed assessment, selected restoration measures often ignore underlying problems at a broader scale and are either ineffective or not cost effective relative to other measures.

A reconnaissance and assessment of watershed character is necessary to:

- Characterize watershed conditions to determine the causes and nature of impairment
- Determine feasibility of using restoration or other management options to meet objectives

In some cases, ecological restoration is the most effective response to impairment; in other cases, restoration may be one among many candidate tools for achieving objectives. To determine the appropriate actions, it is necessary to collect, compile, analyze, and interpret environmental data rapidly to facilitate management decisions and resultant options for preservation and control or mitigation of impairment. This Technical Note presents considerations for watershed and reach reconnaissance techniques that possess the following principal elements:

- cost-effective
- facilitate comparisons among sites
- quick, yet scientifically valid
- easily presented to the public
- environmentally-benign procedures.

Basic Site Characterization

Basic site characterization and data collection are the first steps in inventorying a watershed. Characterization may include information on water quality; geochemistry; hydrology; fluvial geomorphology; substrate condition; flora; and fauna; and, to the greatest extent possible, identification of stressor sources in the watershed. In addition to traditional point source loading of pollutants, stressors may include nonpoint source pollutant loading, land-use effects upon hydrology or sediment yield, physical habitat alterations, and invasion of non-native flora and fauna.

Data collected, including both site and landscape-scale data, also provide a baseline for evaluating the performance of restoration projects. These data can be used to establish the environmental benchmarks to be used later to monitor for success of the restoration practices.

In addition to physical and chemical characteristics of the watershed, land ownership and regulatory jurisdictions play an important role in determining opportunities for restoration. Much of this information is geographically based, and amenable to storage and manipulation in a Geographic Information System (GIS). As part of the basic site characterization, the acquisition of historical and current data on landscape-scale habitat and landuse characteristics as well as land ownership is recommended. This information is useful for (1) setting realistic restoration goals, and (2) identifying regional issues that must be addressed before undertaking a watershed or site-specific restoration project.

Habitat Analysis

Analysis of habitats is important for identifying weaknesses and potential strengths in the habitat structure of the stream being considered for restoration. Regardless of the specific approach used, habitat assessment should:

- facilitate identification of potentially limiting habitat conditions
- provide design guidance regarding “what works" from a habitat perspective in the type of stream being restored
- be repeatable to allow pre- and post-restoration comparison.

Habitat assessment should identify habitat deficiencies by surveying the project site and less degraded comparison or reference sites in the same geographic area. These surveys can be visual, qualitative estimates or can be based upon quantitative measurements. Assessments usually consider such key habitat variables as pool-riffle-run ratio, pool quality, predominant substrate type, substrate embeddedness, available cover, bank structure and stability, water temperature, riparian vegetation type and abundance, and riparian buffer widths.

Habitat assessment for more formal designs often requires quantitative measurements and statistical comparison of conditions at the sampled sites. Most state and federal resource management agencies have aquatic habitat evaluation procedures tailored to local and regional conditions, and may have file data available to assist in defining habitat restoration goals. While many evaluation procedures have been proposed, most of the methodologies fall into one of two general categories on the basis of how the habitat data is collected and analyzed. Basin wide methodologies tend to collect and analyze habitat data on a reach-by-reach basis, frequently using numerical ratings to score specified attributes of habitat quality. Transect methodologies measure specific parameters along cross section transects established in study reaches representative of longer stream segments.

Identify Nature of Impairment

In some watersheds, direct and predictable relationships between watershed character and stream impairment exist. In many cases, however, the connection between sources and impairment is less obvious. A spatial analysis of the specific nature and causes of impairments throughout the watershed is usually not feasible during the watershed inventory. However, an overriding objective of the reconnaissance effort should be to identify and characterize as many cause-effect relationships as possible.
Major causes of degradation of stream habitat include: dams and other water control structures, urbanization, clearing of vegetation along the streambank and immediately adjacent land; access of humans and wildlife to streambank with soil compaction and increased erosion; alteration of the composition of stream-side vegetation through reduction of plant cover; and river-management and transportation works including bank stabilization activities. These activities should be noted and qualitatively evaluated for their impact on available habitat.

Identified impairments must be addressed within the appropriate regulatory context. In some cases, a narrative criterion or designated use component of the water quality standard may explicitly refer to a habitat use, such as the necessity of maintaining spawning habitat. In other cases, the water quality standard in question may not refer explicitly to a habitat goal or function, but rather to some numeric criterion. Restoration may thus address numeric or narrative criteria.

Combining information on watershed physical characteristics, water quality, habitat, land ownership, and regulatory jurisdictions with the preliminary analysis of the nature of impairment allows selection of the best strategies to develop sustainable restoration sites, increase regional biodiversity, and, along the way, suggest the places appropriate for economic development.

Establishing a Standard of Comparison

One of the more important (and difficult) tasks is the establishment of a reference condition that can serve as (1) a target or objective for the restoration project, or (2) as a standard for comparison among candidate sites. Restoration based upon replicating a reference condition (option 1) requires the selection of a desired end condition for the proposed management action. A predetermined standard of comparison provides a benchmark against which to measure progress.

Option 2 is intended to serve as a basis for the relative comparison of degradation and restoration potential among candidate sites and, thus, needn't be a "desired" condition. Project constraints, notably funding availability, generally preclude the implementation of all potential restoration or management options. A means of prioritization is very helpful in selecting sites within a watershed or along a stream reach for which the benefits will be greatest given project constraints.

Historical conditions in the region should be considered when establishing a standard of comparison. If current conditions in a stream corridor are degraded, it may be best to establish the standard at a time period in the past that represented more natural or desired conditions. It is important to agree on what conditions are desired prior to establishing the standard of comparison. In addition, the geographic location and size of the area should be considered. Patterns of diversity vary with geographic location, and larger areas are typically more diverse than smaller areas.

Opportunities for Restoration

Even where good opportunities exist for ecological restoration, establishing whether such techniques are appropriate for further consideration as management options must take into account the technical feasibility of restoration. That is, there will be cases in which ecological restoration opportunities are obvious, yet are not technically feasible with the current state of the science.

When direct, instream ecological restoration does not appear feasible, however, riparian or upland restoration options (generally based on source control in the surrounding watershed) may improve habitat. When restoration by either instream, riparian, or upland techniques appears feasible, the goals for the project must be reevaluated. Consideration of economic viability of candidate restoration techniques should be addressed during the reconnaissance.

Data Collection

The principal author has conducted a number of watershed assessments with the express intent of identifying candidate sites for restoration or other management measures. To ensure consistency in these efforts, he has constructed field sheets for data compilation. Two general categories of data are collected in the reconnaissance efforts, (1) physical data characterizing the watershed, stream, and observed processes, and (2) a qualitative assessment of ecological character. The specific nature of the field data sheets varies by project, but the general form is similar among projects and they are presented here so the reader can adopt a similar strategy.

The strategy used by the author is to divide the stream (and associated watershed) into distinct reaches. Separate data sheets are used for each reach. Factors used in the reach subdivision include:

- General stream character
- Stream stability
- Adjacent landuse
- Property ownership
- Anthropogenic features
- Project objectives
- Riparian condition
- Location of tributaries
- Location of gages
- Access and survey time

The example sheets presented as Appendix B in this handbook and the accompanying field descriptors were for a suburban watershed assessment in Georgia.

Physical Data Sheet Description

Appendix B presents an example form used to document the field conditions observed during the reconnaissance effort. A separate sheet is used for each study reach, and each data sheet includes a summary header section with the study reach denoted by stream name and reach number, starting and ending latitude and longitude, the date of the survey, Gage level on that date (if the stream is gaged), and the name of the surveyor. Check marks are provided for the surveyors assessment of the verity of the reach as a reference. In addition to the data categories described below, space is provided on the sheets to record observations, sketches, and numbers of photographs taken of the subreach.

The first category of data evaluated on the sheet is the **area** and **percent impervious surface** in the watershed. These values can be determined using a GIS Database.

Under the adjacent land use heading are eight classifications. Land use classification is based upon field observation during the reconnaissance survey with verification using aerial photographs. Land use is characterized only for a 100-m corridor on either side of the top of bank. For many of the subreaches, more than one adjacent land use may be noted. In these cases, estimates of the percent distribution of each class should be noted. A list of the classes and their descriptions follow.

Adjacent Land Use (within 100 m of the banks):

Wetland – Sedge dominant or BLH riparian wetlands.
Forest – Predominantly timber.
Agriculture - Crops or pasture.
Parks & Recreation – Trails, golf courses, and parks.
Residential - Single family dwellings or subdivision for lot sale.
Commercial/Industrial - Self explanatory.
Transportation - Roads, rail lines, and bridges.
Utility – Power, telephone, or pipeline right-of-way.

The third category addressed on the field notes is the type of riparian vegetation. Included are eight classes. Riparian vegetation classification is based upon field observation during the survey with verification using the aerial photographs. The classification is limited to the riparian and near overbank zone (about 30 m landward of the top bank). The overbank vegetation classification does not include vegetation below the top of bank. In most cases, percent distribution for each class in the reach should be estimated. The classifications used in these sheets are not proposed for use beyond the purpose of serving the immediate mapping activity. Much more field work and description of vegetation units will be necessary before a more nearly ideal classification can be devised and the areas appropriately classified. A list of the classes and their descriptions follow.

Riparian Vegetation (within 30 m):

Barren - Soil, concrete, or other surface absent any vegetation cover.
Sedge & Grass - Carices or other graminoids dominant; water table at or above ground surface most of growing season; little or no peat accumulation. Does not include non-native herbaceous vegetation.
BLH – Dominated by seasonally-flooded hardwoods including Quercus, and Nyssa.
Shrubs - Shrubs in various native species combinations, including stands of young tree species of shrub size. Most shrub thickets in the study area are made up of broadleaf

species, including orthophyllous deciduous species (willows (*Salix spp*.), alders (*Alnus Spp*.), dogwoods (*Cornus Spp*.), etc.)

Deciduous Forest – Predominantly broad-leaved trees such as oak (*Cornus Spp*.), cottonwood (*Populus Spp*.), elm (*Ulmus Spp*.), etc., in closed- or somewhat open-canopy arrangement. Might include a few evergreen or shrub species, but less than 10 percent of total area.

Coniferous Forest – Predominantly pines (*Pinus taeda, P. echinada, P. virginiana*, etc.,) trees in closed- or somewhat open canopy arrangement. May include a few deciduous tree or shrub species, but less than 10 percent of total area.

Invasive – Non-native nuisance vegetation including kudzu (*Pueraria lobata*) honeysuckle (*Lonicera Spp*.), and privet (*Ligustrum Spp*.).

Non-Native - All non-native herbaceous vegetation, including most lawn.

The next category is a descriptor of the vegetation **cover** characteristics in the reach and includes measures of percent canopy closure over the water and the percent Large Woody Debris (LWD) in the reach.

The fifth category addresses channel characteristics. Included are the channel planform, the profile characteristics (as manifested in the flow conditions), the flow type, and other miscellaneous features that contribute to habitat. Most reaches include one or more meanders and, thus, considerable diversity in many of the channel characteristics. The intent of this effort is to provide some useful information in evaluating overall diversity of the reaches. Summary descriptions of the classifications for each category follow.

Channel Characteristics:

Planform - The general shape of the channel as viewed from above.

Bend - A meander where the channel thalweg is against the outer bank.

Crossing - A short straight reach between meanders with the thalweg not aligned with the banks.

Straight - A long, relatively straight reach where the thalweg is generally parallel with the banks or where there is no discernable thalweg.

Profile - The longitudinal form of the channel; generally defined by the gradient. In this case, riffles, pools, and runs are used to differentiate between profile characteristics because channel slopes were not measured.

Riffle - A reach with a relatively high width to depth ratio, no defined channel thalweg, and a generally higher gradient and velocity, lower depths, and coarser bed material than the mean channel conditions. Usually associated with crossings or straight reaches.

Pool - A reach with a relatively low width to depth ratio, a well defined channel thalweg along one bank, with generally lower gradients and velocities, greater depths, and finer bed material than the mean for the channel. Usually associated with meander bendways.

Run - A reach comparable to a riffle except with a generally lower gradient and lower velocities. Can be associated with either straight reaches of gentle meanders.

Flow Type - A general category describing the flow energy of the system. For this study, only two classes apply (rapid and tranquil) and these are closely related to the profile.

Rapid - High energy, relatively shallow, associated with riffles and high gradient meanders.

Tranquil - Low energy, fairly deep, associated with runs and low gradient meanders.

Features - A general category intended to capture the presence/absence of habitat features and diversity.

Bars - Deposits of sediment located within the channel margins that have a height in excess of the mean water level. Point bars are attached to the bank and associated with bendways whereas mid bars are not attached to the banks and are generally found in straight reaches. Bars are either devoid of vegetation or have only sparse pioneer vegetation occupying less than 25 percent of the surface area of the feature.

Shoals - Deposits of sediment located within the channel margins that have a height less than the mean water level. Shoals are devoid of vegetation, and generally consist of sediments in the coarse sand to small cobble range.

Chutes/Backwater - Channels or partial channels connected to the main channel at flows below the mean water level, but that are not tributaries. Chutes have through flow at flows less than the mean water level whereas backwater features do not.

Snags - Woody debris located within the channel margins at or below the mean water level.

Control - A permanent or semi-permenant structure or feature that causes backwater.

Below the channel characteristics are spaces to note the **stream type** according to the classification proposed by Rosgen (1996) and for the stage of **channel evolution** according to Schumm et al. (1984).

The sixth category documents general **geometric properties** of the reach. Slope and planform characteristics of the reach are determined by field surveys for reference reaches, and interpretation of aerial photographs and USGS 7.5 minute topographic maps for non-reference reaches. Mean widths and depths for the pool and riffle features are estimated in the field by the surveyors based upon random measurement of these features during the site investigation.

The seventh category documented on the field data collection sheets is the characteristics of existing **protection** structures. Insofar as such features were recognizable in the field, their location should be noted on aerial photos, mosaics, or other maps. Information regarding their character and dimension should be noted on the field data sheets. Four principle characteristics should be noted for each structure - the type, height, length, and materials.

The eighth category addresses the bank characteristics that have a bearing upon the general stability and habitat conditions at the water/land interface. The streambank includes the land feature from the top of the bank (as defined by the minimum ratio of the top width/area or the slope break on a rating curve for a section) down to the toe. Included in this section are the height and slope of the upper bank, the soil material in the banks, a general assessment of the bank stability, and the vegetation cover. Measurements of the listed parameters can be made randomly, and the information presented on the data sheets are estimates based upon visual observation and confirmed by the random measurements. Bank material may be difficult to ascertain because of the extent of vegetation cover. A description of the parameters follows.

Bank Characteristics:

Height - The distance (in feet) of the bank above the MHW. Heights are divided into ranges that include 0 – 4 feet, 4 – 8 feet, 8 – 12 feet, and greater than 12 feet.

Slope - The slope of the upper bank based upon visual inspection. Slopes are divided into ranges that include vertical, 1:1, 1:2 (1 foot vertical to two feet horizontal), and 1:3.

Bank Material - A general characterization of the soils found in the bank. No samples were collected and estimates were made on the basis of size classes as follows:

Unknown - Indeterminate due to vegetation or other cover.

Clay & Silt - Soil material smaller than 0.064 mm.

Sand - Soil material ranging in size from 0.064 to 2 mm.

Gravel - Soil material ranging in size from 2 to 64 mm. A few reaches included small cobble material in limited areas and these were included in the gravel fraction.

Bank Status - A general characterization of the current erosional character of the bankline. Where more than one category applied for a given subreach, estimates were made of the percent distribution based upon longitudinal coverage. In some cases, more than one class applied to a given bank and two or more classes were checked without assigning percentages. A description of each class follows.

Protected - A manmade structure or feature is preventing erosion at the site.

Intact- No manmade structures are present or were apparent; bankline is stable.

Weathering - Soil loss is not occurring, but the structural integrity of the banks has been diminished by frost heave, freeze/thaw, piping, or geotechnical failure.

Eroding - Active erosion and bank retreat is occurring at the site.

Advancing - Deposition is occurring on the bank (associated with point bars).

Vegetation Types - An estimate of the coverage (in percent) of the banks of seven classes of vegetation. The vegetation classes are described above.

The ninth category documents the erosion conditions noted in each subreach. Two subcategories are addressed - the extent or location of the erosion and the mechanisms. The nature of the erosional processes in most watersheds are such that many contributory factors affect the erosion and determining which ones are at work in a given subreach is difficult with a limited observation and data collection effort. In particular, the normal sequence of channel evolution that accompanies development often overshadows other erosion processes.

Various visual indicators should be used to evaluate the types of failures. The "Bank Erosion" Technical Note in this series discusses the many factors that contribute to bank erosion and the visual indicators to determine which are predominant. Descriptions of the classes for the two subcategories follow.

Erosion Processes:

Extent

None - No erosion noted in the subreach (stable or accreting).

Toe - Erosion is limited to the toe zone of the bank.

Lower Bank - Erosion is occurring on both the toe and splash zones of the bank.

Upper Bank - Lower bank is intact, but geotechnical failures are occurring above the splash zone.

Whole Bank - Erosion and/or failure is occurring from the toe to the top of the bank.

Mechanism (See "Bank Erosion" section for a more complete discussion)

None - No erosion noted in the subreach (stable or accreting).
Flow Entrainment - Erosion occurring anywhere on the bank as a consequence of soil removal due to flow-induced shear stress.
Piping - Hydraulic and geotechnical failures on the bank above the toe zone as a consequence of groundwater flow removing lenses of soil from the bank.
Shallow Slide - Geotechnical failure on the entire upper bank resulting from oversteepening of a noncohesive bank as a consequence of degradation or removal of material from the bank toe.
Cantilever - Geotechnical failure on the entire bank resulting from removal of material from the bank toe and overburden on the upper or top bank.
Rotational - Geotechnical failure of the entire bank that results in mass wasting of bank material at the toe and a deep failure plane that is concave in shape.
Slab - Geotechnical failure of the top bank and mass wasting of material due to tension cracks in the top bank.
Other - Self explanatory.

The final category addresses the character of the channel **substrate** (sediments). Included are a general characterization of the sediments (percent distribution of each class) as well as the texture and sediment size based upon gradation analyses of select grab samples.

Environmental Assessment
The data collection and assessment sheets used to characterize each study reach includes information in the header to identify the reach and the conditions under which it was surveyed (see Appendix B). In addition, a procedure based upon the EPA's Rapid Bioassessment Protocols (RBP) is used to qualitatively assess the environmental condition. In the example sheet (for a watershed in Georgia), eight categories were used to assess environmental quality. These categories change with the location and objectives of each project.

All habitat parameters are evaluated and rated on a numerical scale of 0 to 20 (highest) for each of the reaches. The ratings are intended only to serve as a gross characterization based primarily upon subjective considerations. Reference conditions could be used to normalize the assessment to the "best attainable" situation, assuming an appropriate reference reach is identified. Descriptions of each parameter and its relevance follows. A set of decision criteria is given for each parameter, as shown on the example sheet in the Appendix.

1. Streambank Epifaunal Substrate/Available Overbank Cover: This includes the relative quantity and variety of natural structures in the stream, such as fallen trees, logs, and branches, large rocks, and undercut banks, available as refugia, feeding, or sites for spawning and nursery functions of aquatic macrofauna. A wide variety and/or abundance of submerged structures in the stream provides the fish with a large number of niches, thus increasing habitat diversity.

As variety and abundance of cover decreases, habitat structure becomes monotonous, fish diversity decreases, and the potential for recovery following disturbance decreases. Snags and submerged logs are among the most productive habitat structure for macro-invertebrate colonization in low-gradient streams.

2. Instream Substrate Characterization: Evaluates the type and condition of bottom substrates found in the reach. Firmer sediment types (e.g., gravel, sand) and rooted aquatic plants support a wider variety of organisms than a substrate dominated by sands and silts or silts and clays. In addition, reaches that have a uniform substrate will support far fewer types of organisms than a stream that has a variety of substrate types. Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are covered by or sunken into the silt, sand, or clays of the stream bottom. Generally, as rocks become embedded, the surface area available to macro-invertebrates and fish (shelter, spawning, and egg incubation) is decreased.

3. Morphological Diversity of Channel and Flow: Diversity is a way to measure the heterogeneity of a stream. Riffles are a source of high-quality habitat and diverse fauna, therefore, an increased frequency of occurrence greatly enhances the diversity of the stream community. For areas where distinct riffles are uncommon, a measure of meandering or sinuosity helps define diversity. A high degree of sinuosity provides for diverse habitat and fauna. A diversity of depths and velocities protects the stream from excessive erosion during flooding and provides refugia for benthic invertebrates and fish. Natural conditions include reaches of moderately shifting channels and bends and stable reaches that do not exhibit progressive changes in slope, shape, or dimensions. Patterns of velocity and depth are included; the best reaches will have all four patterns present: (1) slow-deep, (2) slow-shallow, (3) fast-deep, and (4) fast-shallow.

4. Bank Vegetative Diversity and Condition Above Bankfull: Measures the amount of the stream bank that is covered by vegetation. The root systems of plants growing on stream banks help hold soil in place, thereby reducing the amount of erosion that is likely to occur. This parameter supplies information on the ability of the bank to resist erosion as well as some additional information on the uptake of nutrients by the plants, the control of instream scouring, and stream shading. Banks that have full, natural plant growth are better for fish and macro-invertebrates than are banks without vegetative protection or those shored up with concrete or riprap. This parameter is made more effective by defining the natural vegetation for the region and stream type (i.e., shrubs, trees, etc.). In areas of high grazing pressure from livestock or where residential and urban development activities disrupt the riparian zone, the growth of a natural plant community is impeded. Residential developments, urban centers, golf courses, and rangeland are the common causes of anthropogenic degradation of the riparian zone.

5. Channel Stability (Base Level): This category addresses the stability of the channel profile in terms of the normal stage of evolution channels undergo in response to urbanization. Channels that are actively headcutting (level 2), widening (level 3), or depositional (level 4) generally have degraded habitats when compared to naturally stable (level 1) or stable incised (level 5) channels. Of the three degraded conditions, level 2 stream segments generally offer the best habitat because they tend to have coarser substrates, greater pool depths and velocities, and more diversity, although the life of these features may be limited. Level 4 streams tend to have the worst habitat conditions, but are on the way to recovery.

6. Bank Stability: Measures whether the stream banks are eroded (or have the potential for erosion).

7. Riparian Vegetative Zone Width: Measures the width of natural vegetation from the edge of the stream bank out through the riparian zone. The vegetative zone serves as a buffer to pollutants entering a stream from runoff, controls erosion, and provides habitat and nutrient input into the stream. A relatively undisturbed riparian zone supports a robust stream system; narrow riparian zones occur when roads, parking lots, fields, lawns, bare soil, rocks, or buildings are near the stream bank. The presence of minor paths and walkways in an otherwise undisturbed riparian zone was judged to be inconsequential to destruction of the riparian zone.

8. Riparian Management Potential: Measures the need and attractiveness of preserving existing riparian habitat in a reach or of implementing management measures to improve riparian habitat.

Field Operational Rules

During any field survey there are always numerous decisions to be made; it is important that these decisions are made in a consistent manner. The following operational rules will make field surveys easier by removing procedural ambiguities.

1. Minimum reach length is 1 W_b (bankfull width).
2. Maximum distance along a channel without an assessment is 10 W_b (even if there is no change in the level of disturbance).
3. It is acceptable to break reaches, as determined prior to the initiation of the reconnaissance, into shorter reaches based on field examinations. The new reaches should be identified as a subset of the reach that is being subdivided (e.g., Reach 20 is broken into Reach 20.a and 20.b).
4. As in Rule 1, if a different *type* of channel is encountered it must extend for more than 1 W_b to be included as a distinct subreach.
5. If a tributary, weir, or other feature that dramatically changes the stream character is encountered and the change extends for more than 3 W_b, then a new reach must be designated.
6. If a channel condition not considered in or listed on the field data sheets is encountered, this condition should be added to the sheet for the reach in the notes section.
7. A preliminary reconnaissance of the watershed should be conducted to allow the surveyors an opportunity to formulate a sense of the range of environmental conditions present. This provides a general "reference" so the relative rankings of reaches will be preserved.
8. If a survey requires multiple modes of access (air, boat, wading, walking the banks), every effort should be made to access each reach with every means used for the study.

Data Considerations

Regardless of the type of data being collected, field methods share one important feature in common, they cannot tell you whether the information collected is an accurate portrayal of the system of interest. The properties of a given sample taken from the field may be known with some accuracy, but in characterizing stream and riparian ecosystems we are typically interested in answering questions on much larger spatial and temporal scales. To grapple with this problem, environmental scientists and statisticians have long recognized that field methods must strive to obtain samples and (or) data that are representative of the field conditions at the time of sampling.

An accurate assessment of lotic biological data is difficult because natural variability cannot be controlled. The accuracy of macroinvertebrate assessments, for example, cannot be objectively verified and different techniques may yield conflicting interpretations at the same sites. Depending on which methods are chosen, and the times at which samples are collected, the actual structure and condition of the benthic assemblage present, or trends in the status of the benthos over time, may be misinterpreted.

There are two general approaches for acquiring comparable bioassessment data. The first is for everyone to use the same method on every study by developing standard operating procedures (SOPs). However, the use of a single method, even for a particular type of habitat, is often not feasible because of different requirements among participating agencies. The second approach to acquiring comparable data from different organizations, and to encourage the documentation of quality control characteristics for all methods and to use those characteristics to determine comparability of different methods. This documentation, often called a performance-based method system (PBMS), permits the use of any techniques that meet established requirements for data quality. Data quality requirements usually address data precision, bias, method sensitivity, and range of conditions over which a method yields satisfactory data.

Species Requirement Analyses

A few analytical techniques are available that assist in a determination of how well a system provides for the life requisites of fish and wildlife species. These techniques tend to focus on one or more target species or groups of species. In some cases, the analysis is based on an explicit statement of the physical factors that distinguish good habitat from poor. In more complicated cases, variables including other species that provide food or biotic structure, other species as competitors or predators, or spatial or temporal patterns of resource availability are included.

Analyses based on species requirements explicitly incorporate relations between physical variables and desired biological attributes. In practice, this approach is often compromised by incomplete knowledge of the species habitat requirements. The complexity of these methods varies along a number of important dimensions, including prediction of habitat suitability versus population numbers, analysis for a single place and single time versus a temporal sequence of spatially complex requirements, and analysis for a single target species versus a set of target species. Each of these dimensions must be carefully considered in selecting an analysis procedure appropriate to the problem at hand.

The Habitat Evaluation Procedures (Hep)

Habitat evaluation procedures (HEP) can be used for several different types of habitat studies, including impact assessment, mitigation, and habitat management. HEP provides information for two general types of habitat comparisons—the relative value of different areas at the same point in time and the relative value of the same area at different points in time. Potential changes in wildlife (both aquatic and terrestrial) habitat due to proposed projects are characterized by combining these two types of comparisons.

HEP is based on two fundamental ecological principles—habitat has a definable carrying capacity, or suitability, to support or produce wildlife populations (Fretwell and Lucas 1970), and the suitability of habitat for a given wildlife species can be estimated using measurements of vegetative, physical, and chemical traits of the habitat. The suitability of a habitat for a given species is described by a habitat suitability index (HSI) constrained between 0 (unsuitable habitat) and 1 (optimum habitat). HSI models have been developed and published by the U.S. Fish and Wildlife Service (Schamberger et al. 1982; Terrell and Carpenter, in press), and USFWS (1981) provides guidelines for use in developing HSI models for specific projects. HSI models can be developed for many of the previously described metrics, including species, guilds, and communities (Schroeder and Haire 1993).

The fundamental unit of measure in HEP is the Habitat Unit, computed as follows:

$$HU = AREA \times HSI$$

where HU is the number of habitat units (units of area), AREA is the areal extent of the habitat being described (units of area), and HSI is the index of suitability of the habitat (unitless). Conceptually, an HU integrates the quantity and quality of habitat into a single measure, and one HU is equivalent to one unit of optimal habitat.

HEP provides an assessment of the net change in the number of HU's attributable to a proposed future action, such as a stream restoration project. A HEP application is essentially a two-step process—calculating future HU's for a particular project alternative and calculating the net change as compared to a base condition.

The steps involved in using and applying HEP to a management project are outlined in detail in USFWS (1980a). However, some early planning decisions often are given little attention although they may be the most important part of a HEP study. These initial decisions include forming a study team, defining the study boundaries, setting study objectives, and selecting the evaluation species. The study team usually consists of individuals representing different agencies and viewpoints. One member of the team is generally from the lead project planning agency and other members are from resources agencies with an interest in the resources that would be affected.

One of the first tasks for the team is to delineate the study area boundaries. The study area boundaries should be drawn to include any areas of direct impact, such as a flood basin for a new reservoir, and any areas of secondary impact, such as a downstream river reach that might have an altered flow, increased turbidity, or warmer temperature, or riparian or upland areas subject to land use changes as a result of an increased demand on recreational lands. Areas such as an upstream spawning ground that are not contiguous to the primary impact site also might be affected and therefore should be included in the study area.

The team also must establish project objectives, an often neglected aspect of project planning. Objectives should state what is to be accomplished in the project and specify an end point to the project. An integral aspect of objective setting is selecting evaluation species, the specific wildlife resources of concern for which HU's will be computed in the HEP analysis. These are often individual species, but they do not have to be. Depending on project objectives, species' life stages (e.g., juvenile salmon), species' life requisites (e.g., spawning habitat), guilds (e.g., cavity nesting birds), or communities (e.g., avian richness in riparian forests) can be used.

Physical Habitat Simulation (Phabsim)

The physical habitat simulation (PHABSIM) model was designed by the U.S. Fish and Wildlife Service primarily for instream flow analysis (Bovee 1982). It represents the habitat evaluation component of a larger instream flow incremental methodology for incorporating fish habitat consideration into flow management, presented in Chapter 5. PHABSIM is a collection of computer programs that allows evaluation of available habitat within a study reach for various life stages of different fish species. The two basic components of the model are hydraulic simulation (based on field-measured cross-sectional data) and several standard hydraulic methods for predicting water surface elevations and velocities at unmeasured discharges (e.g., stage-discharge relations, Manning's equation, step-backwater computations). Habitat simulation integrates species and life-stage-specific habitat suitability curves for water depth, velocity, and substrate with the hydraulic data. Output is a plot of weighted usable area (WUA) against discharge for the species and life stages of interest.

The stream hydraulic component predicts depths and water velocities at unobserved flows at specific locations on a cross section of a stream. Field measurements of depth, velocity, substrate material, and cover at specific sampling points on a cross section are taken at different observable flows. Hydraulic measurements, such as water surface elevations, also are collected during the field inventory. These data are used to calibrate the hydraulic simulation models. The models then are used to predict depths and velocities at flows different from those measured.

The habitat component weights each stream cell using indices that assign a relative value between 0 and 1 for each habitat attribute (depth, velocity, substrate material, cover), indicating how suitable that attribute is for the life stage under consideration. These attribute indices are usually termed habitat suitability indices and are developed from direct observations of the attributes used most often by a life stage, from expert opinion about what the life requisites are, or a combination. Various approaches are taken to factor assorted biases out of this suitability data, but they remain indices that are used as weights of suitability. In the last step of the habitat component, hydraulic estimates of depth and velocity at different flow levels are combined with the suitability values for those attributes to weight the area of each cell at the simulated flows. The weighted values for all cells are summed to produce the WUA.

There are many variations on the basic approach outlined above, with specific analyses tailored for different water management phenomena (such as hydropeaking and unique spawning habitat needs), or for special habitat needs (such as bottom velocity instead of mean column velocity) (Milhous et al. 1989). However, the fundamentals of hydraulic and habitat modeling remain the same, resulting in a WUA versus discharge function. This function should be combined with the appropriate hydrologic time series (water availability) to develop an idea of what life stages may be impacted by a loss or gain of available habitat and at what time of the year. Time series analysis plays this role, and also factors in any physical and institutional constraints on water management so that alternatives can be evaluated (Milhous et al. 1990).

Several things must be remembered about PHABSIM. First, it provides an index to microhabitat availability; it is not a measure of the habitat actually used by aquatic organisms. It can be used only if the species under consideration exhibit documented preferences for depth, velocity, substrate material, cover, or other predictable microhabitat attributes in a specific environment of competition and predation. The typical application of PHABSIM assumes relatively steady flow conditions such that depths and velocities are comparably stable within the chosen time step. PHABSIM does not predict the effects of flow on channel change. Finally, the field data and computer analysis requirements can be relatively large.

Riverine Community Habitat Assessment and Restoration Concept (RCHARC)
Another modeling approach to aquatic habitat restoration is the Riverine Community Habitat Assessment and Restoration (RCHARC) concept. This model is based on the assumption that aquatic habitat in a restored stream reach will best mimic natural conditions if the bivariate frequency distribution of depth and velocity in the subject channel is similar to a reference reach with good aquatic habitat. Study site and reference site data can be measured or calculated using a computer model. The similarity of the proposed design and reference reach is expressed with three-dimensional graphs and statistics (Nestler et al. 1993, Abt et al. 1995). An adaptation of this concept by Fischenich (1999) is the Fish Index of Suitability (for Habitat), or FIS(H). This model permits multivariate comparisons of frequency distributions for any number of physical or chemical variables and has been shown to provide a higher resolution than RCHARC.

4 Analyzing Streambank Erosion

A disciplined and detailed approach to fieldwork for bank assessment is the basis for sound identification and characterization of the site and its problems. A consistent methodology should be applied to observe, record, and identify channel processes and existing conditions. Experience has shown that the methodology can be mastered and performed quickly and that it does provide suitable documentary information to support decision making with regard to the most appropriate approach to dealing with a bank problem. While the watershed assessment is not without cost, it is very cost effective when the implications of misidentification of site and processes is considered.

Schedule and budget restrictions often put pressure on study mangers minimize the effort expended on this step. However, it is important to recognize that investing a few days of staff time at the outset of a project to assess historical information held in the office, and in performing stream reconnaissance in the field, can produce very substantial efficiency gains later in the study. This is the case because an accurate evaluation of the bank problem supports the selection of the most appropriate option or response. This can help avoid implementing ineffective bank management strategies, over-designing bank structures that generate unnecessary expenditure and excessive environmental impacts, and under designing structures that subsequently fail.

Problem Identification

Physical, Chemical, Biological, and Sociological Relations

Ecological systems are groups of interacting, interdependent parts (e.g., species, resources) linked to each other by the exchange of energy, matter, and information. Ecological systems are considered complex because they are characterized by strong interactions among components, feedback loops, significant time and space lags, discontinuities, thresholds, and limits.

Three tenets of ecological hierarchy (component patterns and processes) are required for an understanding of landscape patterns and their dynamics:

- Every component of an ecosystem, ecological or otherwise, is a whole and a part at the same time.
- Patterns, processes, and their interactions can be defined at multiple spatial and temporal scales.
- There is no single scale of ecological organization that is correct for all purposes.

Symptoms and Causes

Simply stated, streambank stabilization and restoration projects will be successful only if they are targeted at the specific cause of the instability, or if the designer is very lucky. Field observations are necessary, but not always sufficient, in the interpretation of bank erosion problems. A seven-step process to identify and document site conditions and the symptoms of bank failure are presented below. Though the process of linking symptoms with causes occurs concurrently with the field assessment, additional analyses subsequent to the site investigation are sometimes necessary.

Step 1 - Scope and purpose

Field time can be relatively expensive. To be cost-effective, an effort should be made to determine the general processes at work in the system. The field team can make some initial planning level decisions if the general goals and potential project types are also decided on prior to the fieldwork. Before setting out, the field team should acquire the relevant survey map(s), geologic maps and, if available, an aerial photograph of the study reach. The setting revealed by these simple sources of spatial data are crucial to understanding the nature and wider context of a bank stability problem.

In selecting the team to undertake the fieldwork, a person with local experience and background knowledge of the location is usually essential. The field visit is only able to present a snapshot in time and the value of the record is enhanced by comments from someone with experience of the site. At least one member of the team should have had some training in geomorphology and some prior experience of using the bank assessment sheets. The team should also have design experience with the potential project types to make optimum use of their time.

Experience shows that the quality of the whole exercise improves when the team has a clear, common understanding of the problem being addressed and the purpose of the fieldwork. Consequently, a briefing to appraise the team of the problem and the main issues must be given before the field assessment. The team should examine the worst and best sites together with the sponsors. The team must record a problem statement and note the purpose of the assessment at the outset, together with details of the logistics of the field investigation. Not only does this concentrate their minds, but also it helps to put the results into context when subsequent investigators use the bank assessment document as a historical record of conditions at the site. If different teams are utilized on the same study, it is recommended that they calibrate their observations by examining a few sites together and as the study progresses, periodically check one another.

Step 2 - Summary Sheet

Once the general goals, dominant processes, and potential projects are identified, a standard summary field sheet should be developed. This summary sheet draws together the observations and interpretations to produce a synopsis that can be used by planners, policy makers, river managers and designers of bank protection structures. Using a data sheet, which is standardized for the particular study, will serve to insure consistent observations and assessments. The summary sheet is divided into short statements describing: the general condition of the bank and the location, the extent and severity of bank problems; the primary and tertiary processes and mechanisms driving bank retreat; probable cause(s) of the problem, and suggestions for solution through changes of bank management or appropriate structural intervention.

The third step is to explore the river and riparian zone around the problem location and establish the lie of the land, significant natural and artificial features of the floodplain, and the morphology of the channel. These features are best sketched on a site map together with representative cross-section(s). Note that space is provided in all of the sample sheets in Appendix A for sketches. The site map may be sketched by hand, but often it is much better to work directly on to an Ordnance Survey map of appropriate scale for this purpose. It is important to use the symbols given in the key in order that features noted in one survey can be properly interpreted by different operators in subsequent surveys. It is also important to develop a uniform and consistent reach numbering system for the recorded data to avoid confusion once the data is analyzed in the office. Also, the locations of any site photographs must be noted on the map if they are to form a really useful record for future reference.

Step 4 - Bank survey

The forth task is to describe the form and features of the river bank in terms of the bank characteristics (including material properties and layering, profile geometry, the bank protection status and presence of cracks or fissures), bank structures and bank vegetation. Each of these characteristics is of fundamental importance to the selection of appropriate techniques to solve the bank problem. Space is provided for notes on important morphological features of the bank.

Step 5 - Bank problems

The fifth task is to establish the location, extent and severity of the particular problem experienced by the bank at the site, or along a river reach. Bank erosion processes and geotechnical stability are treated separately in line with the established fact that each requires separate consideration when selecting appropriate solutions. This stage contrasts with the previous ones in that as well as keen observation and recording of features, a degree of interpretation is required through which the geomorphological process is inferred from bank form. In the record sheets, observations are noted separately from interpretations and the team can assign a level of confidence to their interpretative record based on their degree of experience and self-assurance. It is recommended that the field teams initially examine the best and worst sites in the watershed with the local sponsor before conducting a watershed characterization so to calibrate their observations with expected geomorphic conditions.

Step 6 - Bank toe condition

This step concentrates observations and their interpretation on a crucial area - the toe of the bank. The form of the bank profile at the toe, the presence or absence of debris from bank erosion or failures stored in the form of a berm or spending beach, and the type and age of vegetation are recorded. These observations give important clues about whether the bank toe is being actively undercut by the river currents and/or wave action, or is accumulating sediment due to retreat that is being driven by processes operating within or behind the bank. Identification of whether the driving processes of retreat are derived from the river side or the floodplain side of the bank is absolutely essential if a solution based on bank management or soft protection is to be recommended.

Step 7 - Bank map and profiles

Completion of this, the final step, actually runs in parallel with steps 4, 5 and 6. It consists of the production of a detailed bankline map and representative profiles that show the spatial relationship between various morphological forms and features noted on the record sheets.

Good use may be made of photographs and field sketches to supplement the information recorded on the map. However, experience shows that that the value of photographs is increased enormously if the locations and orientations of all site photographs are shown on the site and bankline maps. This is helpful in examining photographs afterwards, and it is invaluable on subsequent site visits when attempting to use the photographs to identify channel and bankline changes.

Data Requirements

Data Needs

Data needs vary depending on the scope and nature of the project, but in general it is necessary to compile sufficient data to allow the design team to formulate an understanding of the processes occurring at the site and within its basin. At least some level of understanding must exist for all four ecosystem components: water quality, biological, physical, and sociological.

Existing Data

Much of the data needed for a typical restoration or streambank stabilization project has already been collected by others. Table 4.1 presents sources for many types of information useful in developing restoration and stabilization projects.

Daily mean streamflow data needed for defining flow duration curves are published on a water-year (October 1 to September 30) basis for each state by the U.S. Geological Survey (USGS). The data collected and published by the USGS are archived in the National Water Data Storage and Retrieval System, which is a computerized data base widely known by the acronym WATSTORE. The USGS also provides access to streamflow data by means of the Internet. The USGS URL address for access to streamflow data is http:/water.usgs.gov/index.html. Approximately 400,000 station years of historical daily mean flows for about 18,500 stations are available through this source.

In addition to the daily mean flows, summary streamflow statistics are also published for active streamflow stations in the USGS annual Water Resources Data reports. Among the summary statistics published by USGS are the daily mean flows that are exceeded 10, 50, and 90 percent of the time of record. Annual peak flow data needed for flood frequency analysis are also published by the USGS and archived in WATSTORE and available through the internet at the URL address described above.

Table 4.1 Sources of data

Data Description	Possible Sources
Map and Charts	
Topographic	***USGS, State DOT***
Soils	***USGS, NRCS, Soil Cons. Districts***
Geologic	***USGS***
Land Use, Zoning	***USCOE, USBOR, FEMA, City/County***
Aerial Photographs	
Color, IR, & B&W Aerial	***USBOR, USFWS, NRCS***
Hydraulic and Hydrologic	
Discharge Records	***USGS, USBOR, USCOE, USFS***
Stage Records	***USGS, NWS, USFS***
Velocity Records	***USGS, USBOR, USFS***
Sediment Data	
Type	***USGS, USCOE, USBOR***
Gradation (bed, susp., bank)	***USGS, USCOE, USBOR***
Climatologic Data	
Precipitation Records	***NWS***
Temperature Records	***NWS***
Vegetation	
Type and Age	***USFWS, NRCS, Universities, USFS***
Distribution	***USFWS, NRCS, Universities, USFS***
Geomorphic	
Basin Geology	***USGS, USBOR, Universities***
River Characteristics	***USGS, USCOE, USBOR, USFWS***

Field equipment

Recommended minimum field equipment for conducting a site assessment include:

- map and aerial photographs showing channel reaches to be evaluated in the field
- topographic map of study area
- field guidebook and notebook with field data sheets
- chest waders
- 50 m or larger cloth tape measure
- folding ruler
- soil probe
- basic surveying equipment to approximate channel slope including a hand-held level (e.g., Suunto clinometer, locklevel) and survey rod (stadia or pocket)
- 35 mm camera and 200 ASA (or faster) film

- channel "types" and other classification "keys"
- sediment size classification “keys”
- machete
- first aid kit

Data Collection Techniques

Reach Selection

The intended use of the cross section analysis plays a large role in locating the reach and the cross section. The section can be located in either a short critical reach where hydraulic characteristics change or in a reach that is considered representative of some larger area. The reach most sensitive to change or most likely to meet (or fail to meet) some important condition may be considered a critical reach. A representative reach typifies a definable extent of the channel system and is used to describe that portion of the system.

Once a reach has been selected, the channel cross section should be measured at the location considered most suitable for meeting the uniform flow requirements of Manning’s equation. The uniform flow requirement is approached by siting the cross section where channel width, depth, and cross-sectional flow area remain relatively constant within the reach, and the water surface slope and energy grade line approach the slope of the streambed. Typically, this location will be at a riffle. For this reason, marked changes in channel geometry and discontinuities in the flow (steps, falls, and hydraulic jumps) should be avoided. Generally, the section should be located where it appears the streamlines are parallel to the bank and each other within the selected reach. If uniform flow conditions cannot be met and backwater computations are required, defining cross sections located at changes in channel geometry is essential.

Channel Cross Section and Profile

The basic information to be collected in the reach selected for analysis is a survey of the channel cross sections and water surface slope, a measurement of bed-material particle-size distribution, and a discharge measurement. The US Forest Service has produced an illustrated guide to field techniques for stream channel reference sites (Harrelson et al. 1994) that is a good reference for conducting field surveys.

The cross section is established perpendicular to the flow line, and the points across the section are surveyed relative to a known or arbitrarily established benchmark elevation. For initial field assessments, a trapezoidal approximation for the section is often sufficient. However, if time and budget permits, a more detailed surveyed section is preferable. The distance/elevation paired data associated with each point on the section may be obtained either by sag tape, rod-and-level survey, hydrographic surveys, or other methods. For most applications, a tenth of a foot precision is sufficient.

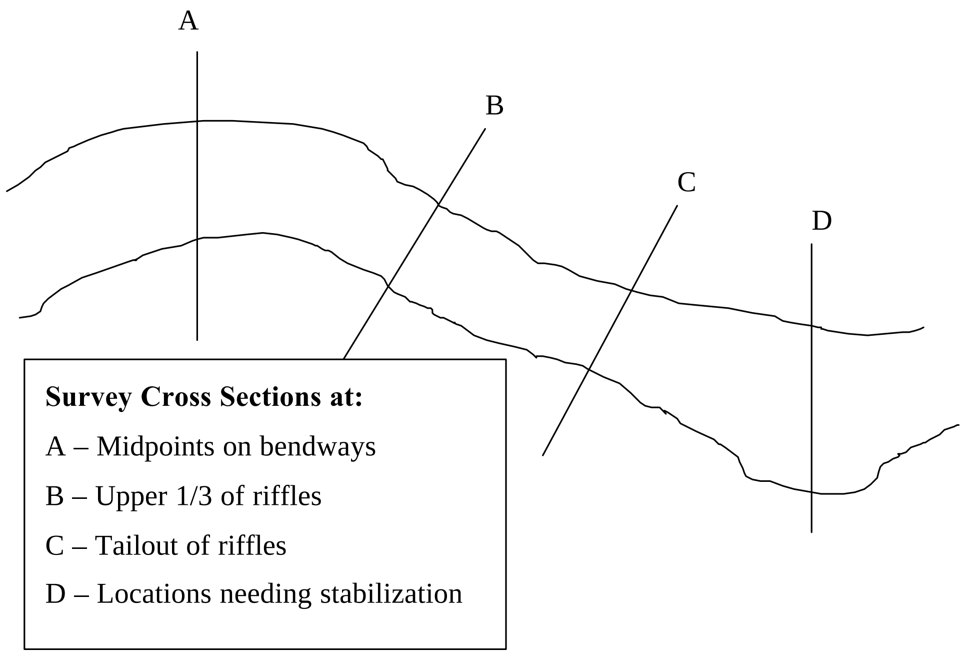


Figure 4.1 Cross Section Locations

An estimate of water surface slope also is required for stability analysis. The survey of water surface slope is somewhat more complicated than the cross section survey in that the slope of the water surface at the location of the section (e.g., pool, run, or riffle) must be distinguished from the more constant slope of the entire reach. Water surface slope in individual channel reaches may vary significantly with changes in stage and discharge.

The low-water slope may be approximated by the change in elevation over individual channel reaches, approximately one to five channel widths in length, while the high-water slope is obtained by measuring the change in elevation over a much longer reach of channel, usually at least 15 to 20 channel widths in length. For initial field assessments, it is recommended that a single slope be determined from the bed at consistent amplitude between riffles. Specifically, from top of riffle to top of riffle or tail of riffle to tail of riffle. It is important to recognize that there will be a natural inclination of the field team to select the closer spaced riffles so the slope may be high.

Velocity & Streamflow Measurement

Streamflow and velocity characteristics are extremely significant factors in developing erosion control and restoration strategies. Direct measurement of streamflow and velocity in the project area is the best way to establish these important parameters. It is not feasible to gage every location where flow data is desired along a river network. Three alternatives are available when the project must proceed without delay. They are, in general order of preference: extend information from nearby gaging sites, estimate streamflows from precipitation data, and make general estimates using an empirical approach. It is important to recognize that each has advantages and limitations. The use of gages is limited to sites having the same general watershed characteristics. Modeling is suitable for evolving watersheds and as a predictive tool but event calibration is recommended to provide confidence in the results. Empirical relationships are easily applied but an assessment of the conditions that they were derived for should be considered and the width of their confidence limits should be assessed.

The basic piece of data obtained at a station is the stage, which is the height of the water surface above a reference elevation. If the stage of the streambed is known and is subtracted from the water-surface stage, then the result is the depth of water in the stream. Although stage of a stream is useful in itself in planning uses of flood plains, most users of streamflow data need to know the discharge of the stream. Discharge is defined as the volume of flow passing a specified point in a given interval of time and includes the volume of the water and any sediment or other solids that may be dissolved or mixed with the water. The units of discharge usually are measured in cubic feet per second (or cubic meters per second, if metric units are used). Discharge is derived from the stage data through the use of a relation between stage and discharge. The stage-discharge relation for a specific stream location is defined from periodic discharge measurements made at known stages. Standard methods of data collection are used as described in the publication series Techniques of Water-Resources Investigations of the U.S. Geological Survey. Those methods are briefly described in the following sections.

Figure 4.2 Measuring velocity and bedload sediments

Measuring Stage

Perhaps the most common method of measuring the stage of a river is through the use of a stilling well. Stilling wells are located on the bank of a stream or on a bridge pier and are topped by a shelter that holds recorders and other instruments associated with the station. The well is connected to the stream by several intakes such that when the water level changes in the stream, the level simultaneously changes in the well. Thus, the water surface in the well is maintained at the same level (stage) as the water surface in the stream. The well damps out the momentary fluctuations in the water surface in the stream due to waves and surging action that may be present in the river. An outside reference gage, typically a graduated staff gage, is read periodically to verify that the water level in the well is indeed the same as the water level in the stream and that the intakes are not plugged. As the water level in the well rises or falls, a float in the well also rises or falls. A graduated tape or beaded cable attached to the float and with a counterweight on the other end is hung over a pulley. This pulley drives a recording device. Historically, the recording device would have used a pen that recorded a graph of the river stage as it changed with time. Graphic recorders are still in use; today, however, the stage is more commonly recorded on a punched paper tape or an electronic recorder or is transmitted to the office by means of satellite.

In many cases, stilling wells are impractical because of difficulties either in installation or operation. Stations that use a bubbler system are an alternative because the shelter and recorders can be located hundreds of feet from the stream. In a bubbler system, an orifice is attached securely below the water surface and connected to the instrumentation by a length of tubing. Pressurized gas (usually nitrogen or air) is forced through the tubing and out the orifice. Because the pressure in the tubing is a function of the depth of water over the orifice, a change in the stage of the river produces a corresponding change in pressure in the tubing. Changes in the pressure in the tubing are recorded and are converted to a record of the river stage.

Crest stage gauges can be used to measure the flood crest under conditions of transient flow. Inexpensive crest gauges can be made using 3-in-diameter PVC pipes with open, screened bottoms and vented tops that are mounted vertically on posts buried in the channel or to existing structures such as bridge piers. Each gauge should contain a removable 1 in x 1 in x 4 ft wood staff wrapped with an adhering cloth and held in place by a cap on the pipe. Finely ground styrofoam pieces are placed at the bottom of the PVC pipe, where they are retained by the screen. When a flood wave passes, the water rises through the screen and lifts the styrofoam (as well as silt and other material); when the water recedes, the styrofoam is left clinging to the staff at the crest stage.

The gauges should be checked after every large precipitation event. Any flood-crest marks are measured and recorded. The current elevation of the channel bed surface relative to a reference elevation marked on each gauge should also be measured. Gauges can be reset after every peak flood event by removing all debris from the staff and restocking the styrofoam pieces as necessary.

Measuring Discharge

The most practical method of measuring the discharge of a stream is through the velocity-area method. This method requires the physical measurement of the cross-sectional area and the velocity of the flowing water. Discharge is determined as the product of the area times the velocity. Velocity is measured by using a current meter. The meter consists of a propeller that is rotated by the action of flowing water. The rotation depends on the velocity of the water passing by the propeller. With each complete rotation, an electrical circuit is completed and recorded in some fashion. Given the number of revolutions in a given time interval, velocity can be determined for the location of the current meter.

Measuring the average velocity of an entire cross section is impractical, so the method uses an incremental method. The width of the stream is divided into a number of increments; the size of the increments depends on the depth and velocity of the stream.

The purpose is to divide the section into about 25 increments with approximately equal discharges. For each incremental width, the stream depth and average velocity of flow are measured. For each incremental width, the meter is placed at a depth where average velocity is expected to occur. That depth has been determined to be about 0.6 of the distance from the water surface to the streambed when depths are shallow. When depths are large, the average velocity is best represented by averaging velocity readings at 0.2 and 0.8 of the distance from the water surface to the streambed. The product of the width, depth, and velocity of the section is the discharge through that increment of the cross section. The total of the incremental section discharges equals the discharge of the river.

When the stage is low and the stream can be waded, the measurements are made by wading with the current meter mounted on a wading rod. The meter is positioned at the appropriate depth on the wading rod, which also is used to measure the water depth. If the water is too deep for wading, then the measurement is made either from a bridge or cableway across the stream. If the measurement is made from a bridge or cableway, then the meter is suspended on a thin cable wound on a reel. A torpedo-shaped weight is attached below the meter to permit it to be lowered into the water and to hold it in position once submerged. If measuring from a bridge, then the reel is mounted on a wheeled frame (or crane) that permits the lowering of the meter assembly over the bridge rail; from a cableway, the reel is mounted in a cable car suspended from the cableway that crosses the river. The basic procedure of measuring width and velocity is the same, however, whether the measurement is made by wading or from a cableway or bridge.

Sometimes, current-meter measurements are not possible during large floods. However, the stage and discharge of those floods are essential in defining the rating for the range of flow. Therefore, the discharge is determined indirectly by surveying the high-water marks left by the flood and by using hydraulic formulas to calculate the discharge for the peak stage.

Because the relation between stage and discharge may vary with time, the discharge is known only with certainty at the time of discharge measurements. If the relation is changing, then judgement must be used to determine the most probable status of the stage-discharge relation for times between discharge measurements. In fact, changes in the stage-discharge relation may not be evident until a whole series of measurements are available for analysis. Therefore, the computational process usually goes through the following steps:

1. Following a measurement, a preliminary evaluation is made of the degree to which the stage-discharge relation has changed on the basis of measurements made up to that time. Provisional discharges are determined, assuming that the most recent measurements define the channel condition.

2. This process is repeated following each measurement. However, with each measurement, more measurements are available to evaluate the stage-discharge relation. This may lead to changes in the provisional discharges that had been computed for previous months.

3. At the end of the sampling period, the entire set of measurements are used to reevaluate the rating conditions. Final decisions are made about the stage-discharge relation that were in effect during the period and the record is refined or recomputed as necessary.

Aerial Photography

Aerial photos are very helpful for delineating floodplain features, geologic history, physiographic features, and structural features such as faulting. They are also useful for comparing channel conditions and meandering of a river over time and for noting the extent of channel changes, extent of flooding and flood damage, low-water conditions, bank erosion and deposition, and changes in land use on the overbank. Areal photography can be very useful in assessing watershed development trends. The use of aerial photography is highly dependent on the scale of the photographs. Typically, large scale aerial photographs is of limited use for the assessment of instream habitat conditions and for the assessment of small streams in wooded areas.

The U.S. Geological Survey's (USGS) Earth Science Information Center (ESIC) maintains an informational data base of aerial photographic coverage of the United States and its territories.

This information describes photographic projects from the USGS, other Federal, State, and local government agencies, and commercial firms. On receipt of the completed checklist and your marked map, ESIC representatives will assist you in locating and ordering photographs (call 1-800-USA-MAPS for more information).

The National Aerial Photography Program (NAPP) scenes on this page (NAPPB Roll 8, Frame 3, 1:40,000 scale film) show a portion of an original 9- by 9-inch photograph and the results obtained by enlarging a section of the original photograph two and four times. NAPP photography can be researched and ordered online using WebGLIS, accessed through the USGS homepage at "http://www.usgs.gov".

Geologic Studies

Geologic investigations define the underlying rock line and provide basic information on channel morphology, characteristics of alluvial deposits, bank stability, suitability of sites for major structures, availability of construction materials, and so on. Geologic history impacts a stream both directly and indirectly through influence on other streambank variables. Geologic conditions are responsible for the quantity and quality of sediment available for transport. Streambank and bed material dictates the location and rate of bank failure. Geologic conditions influence stream slope, entrenchment, aggradation, and degradation.

A geologic and seismologic assessment program might include field borings and surveys to determine general geologic characteristics of the site and in the area, including locations and characteristics of active faults. The extent of the exploration program depends on the geological complexity of the site and the size and type of the project. The edaphic component of geologic assessments includes all the following soil attributes:

- proportions of sand, silt, clay
- gravel content
- organic material
- permeability
- drainage potential
- erodibility

When considering soil properties, it is important to distinguish between soil properties as they relate to the biological functioning and soil properties as they affect the geotechnical function and design. Soil properties vary along elevational gradients and should be tested along any gradients in order to obtain complete results (Reese and Moorhead 1996). The site may require other soil amendments such as lime, gypsum, or other special nutrients depending upon the soil's pH and fertility. Soil tests should be conducted prior to revegetation to determine any amendments needed.

In addition to ensuring proper bank slopes and bank toe protection, attention should be given to the edaphic component that may in turn require some site preparation activities. It is desirable to have slopes covered with at least a 15-cm layer of topsoil high in organic matter; this can be stockpiled prior to any grading. Movement of soil, however, is expensive and must be considered in light of the economic practicality. In lieu of moving rich topsoil, the existing substrate may be amended with fertilizer and mulch to help produce a better soil. In any case, plants need a growing medium that supports the plant and facilitates nutrient and water uptake.

The top layer of soil, about 6 to 24 inches, will provide structure, water and nutrients for rooted wetland vegetation. Although many riparian plants are able to tolerate a wide range of soil properties, a fertile sandy loam or clay loam will allow for easy root and rhizome penetration and good production. A top soil should be high in organic matter and ideally have good aggregate structure for better water and air flow as well as root penetration. Organic matter has a high cation exchange capacity which makes the soil more nutrient-rich.

In the surface soil it is important to provide qualities that will encourage plants to develop healthy root systems and that will support high above-ground production. Clay soils will retain water better than coarser materials but will also impede root and rhizome penetration and will hold water tightly making it less available for plant roots. Plants may not be able to spread when planted in heavy clay soils. Sandy soils are generally low in nutrients and may drain excessively but do allow water to reach roots easily and do not impede root penetration.

Wetland Soils

Although wetland soils can be as diverse as upland soils, soils that develop in frequently saturated or flooded areas tend to develop certain distinguishing characteristics. The presence of organic matter influences several soil physical and chemical properties. A comparison between organic and mineral soils is provided in Table 14. Organic matter is less dense than mineral soil so the porosity is greater with more organic matter and the bulk density is reduced. Organic matter influences many chemical characteristics of the soil and in particular has a high capacity to hold and exchange cations, including nutrients such as calcium and magnesium but dominated by hydrogen. In mineral soils, organic matter will increase the ability of the soil to form aggregates and therefore increases porosity in fine-textured soils.

Table 4.2 Comparison between typical organic and mineral soil properties. (Adapted from Mitsch and Gosselink 1993).

Characteristic	***Organic Soil***	***Mineral Soil***
Organic matter	more than 20 percent (or more than 12 percent with low clay content)	less than 20 percent (or less than 12 percent with low clay content)
Bulk density	0.2 to 0.3 g/cc	1.0 to 2.0 g/cc
Porosity	80 percent or more	45 to 55 percent
Hydraulic conductivity	decreases with decomposition, typically lower than mineral soils other than clay	Higher with coarser texture, generally higher than organic soils
Water-holding capacity	High	Low
Nutrient availability	normally low	Generally high
Cation exchange capacity	high, dominated by H+	low, dominated by Ca, Mg, K, and Na cations

Even when organic accumulation is relatively low, mineral soils in wetlands are distinct from those in uplands. On the surface, wetland soils often develop a layer of very dark or black soil which is high in organic matter. Below this layer, wetland soils generally lack well-developed horizons. If the soil is continuously saturated, it typically develops a grey to greenish-grey color as a result of a process called gleization. Wetland soils develop distinct characteristics due to the oxygen-deficient or reducing conditions.

In delineating a wetland, the soils are examined for indicators such as mottling and oxidized rhizospheres to determined the limits of the wetland soil area. Soils that formed in wetlands are classified as hydric even if the hydrology has changed and there is no longer a wetland. A hydric soil is defined as a soil that is saturated, flooded or ponded long enough during the growing season to develop anaerobic conditions. If the soil is drained, it is still classified as a hydric soil. The general categories of hydric soils are: 1) organic soils (histosols); 2) poorly drained soils with high water tables for at least a week during the growing season; 3) soils that are ponded for long duration during the growing season; and 4) soils that are flooded for long duration during the growing season.

Bank Recession Rates

To develop an effective program for bank stabilization and channel rectification, an understanding of the complex historical pattern of channel migration and bank recession of the stream is essential. A relationship between channel changes and streamflow can be formulated with this information. Studies of bank failure, based on survey data and aerial photographs, provide information on the progressively shifting alignment of a stream and are basic to laying out a rectified channel alignment.

Sedimentation

Investigating potential sedimentation problems such as scour, aggradation and degradation requires an evaluation of the particle-size distribution of the bed material of the stream. For streams with no significant channel armor and bed material finer than medium gravel, bed material samplers developed by the Federal Interagency Sedimentation Project (FISP 1986) may be used to obtain a representative sample of the streambed, which is then passed through a set of standard sieves to determine percent-by-weight of particles of various sizes. The cumulative percent of material finer than a given size then may be determined.

Particle-size data are usually reported in terms of d_i, where i represents some nominal percentile of the distribution, and d_i represents the particle size, usually expressed in millimeters, at which i percent of the total sample by weight is finer. For example, 84 percent of the total sample would be finer than the d_{84} particle size.

In steep rivers with substrate much coarser than medium-gravel, a pebble count, in which at least 100 bed-material particles are manually collected from the streambed and measured, is used to measure surface particle size (Wolman 1954). At each sample point along a cross section, a particle is retrieved from the bed, and the intermediate axis (not the longest or shortest axis) is measured. The measurements are tabulated as to number of particles occurring within predetermined size intervals, and the percentage of the total number in each interval then is determined. Again, the percentage in each interval is accumulated to give a particle-size distribution, and the particle-size data are reported as described above. Additional guidance for bed material sampling in coarse-bed streams is provided in Yuzyk (1986). If an armor layer or pavement is present, standard techniques may be employed to characterize bed sediments, as described by Hey and Thorne (1986).

The scour chain method can be used to monitor scour and fill. Scour refers to the movement of bed material during a flood, and fill refers to sediment deposition that occurs as flood waters subside and fill in scoured areas. To measure scour and fill, scour chains are installed in the channel bed. These are metal chains anchored onto metal plates and buried vertically in the channel bed. When a flood scours away the bed material, the exposed chain falls flat, forming a bend. Subsequent filling reburies the chain. The amount of scour can then be determined by comparing the original length of chain buried to the length left below the bend, and the amount of fill determined by measuring the depth of sediment above the bend. While the use of a scour chain can provide important information, it is important to keep in mind the time required to obtain long term information when developing the scope of a study.

Groundwater

Groundwater is a significant controlling factor in the location and survival of phreatophytic vegetation and its associated wildlife populations. Knowledge of the subsurface water level at a riparian site may be critical to interpretation of vegetation data, and can be a valuable monitoring tool. Maps of groundwater changes can be prepared from measurement of water levels in wells. Water levels in aquifer systems that are in a state of equilibrium between long-term recharge and long-term natural discharge plus human withdrawals will exhibit normal seasonal fluctuations reflecting dry and wet periods of the year, with little change in elevation over long periods of time. In aquifer systems that are in a state of disequilibrium, long-term monitoring will reveal significant changes in the groundwater levels.

Riparian Plant Community Inventory

Plant communities provide most of the components of riparian habitat that are of critical importance to wildlife. The vegetation data should enable future inventories to quantify changes in streamside plant communities. Four parameters are generally required: diversity, density, trunk diameter and percent cover.

Methods used to locate sample plots and inventory riparian plant communities at each study site should be based on procedures established by the U.S. Bureau of Land Management (Myers 1989) and the U.S. Forest Service (Platts et al. 1987). Vegetation data should be collected by establishing sample plots extending from the transect lines used to collect channel morphology data.

Distinct plant communities and their extent along each transect should be identified based on vegetation structural classification parameters (diversity, size, and quantity of vegetation) and landscape features. In order to represent the central tendency of each plant community and minimize influences from adjacent communities, sample plots should be situated within homogeneous plant communities, and transitional areas near community borders (ecotones) avoided (Platts et al. 1987).

Surveys and Mapping

River engineering typically requires some surveying and mapping, particularly where detailed analysis or design is needed. Map scale varies with detail needed for layout of structures. In steep terrain, scales of 1 in. = 400 ft. to 1 in. = 100 ft. with contour intervals of 10, 5, or 2 ft. are appropriate. In flat terrain 1-ft. contours are usually needed.

A permanent second-order horizontal control line (base line) is usually established throughout the study area along one bank and above the water surface for use in layout and construction and as a reference for periodic resurvey of channel cross-sections. The line should be monumented, and elevations of the monuments established.

For major channel rectification and stabilization work, permanent ranges, or sections, across the river are usually needed at a minimum of 5 channel width intervals. Such ranges are tied to the horizontal base line. Profiles across all of the ranges, or selected ranges, are needed intermittently through the study period, during construction, and for operation and maintenance after completion of construction. Information on characteristics (shape, width, depth) of river reaches that are relatively stable in their natural condition can be helpful if it may be assumed that similar cross sections achieved with man-made structures (dikes and revetments) will also tend to be stable.

Construction surveys should be made to control feature project location in the field. Stakes should be set to mark the limits of work, locate structures, establish final grade and alignments, and so on. Post-construction surveys made for preparation of as-built drawings immediately following completion of construction and later for general operation and maintenance work, such as maintenance dredging and repair of structures, are recommended.

Hydrology and Hydraulics

Hydrology is the scientific study of the water of the earth, its occurrence, circulation and distribution, its chemical and physical properties, and its interaction with its environment, including its relationship to living things. Hydraulics is a branch of applied mechanics that deals with the behavior of fluids. Understanding the hydrologic and hydraulic character of a stream is an absolute requirement for successful implementation of virtually any restoration or streambank stabilization project.

Runoff

Gaged Sites: At gaged locations, flood volumes are estimated directly from records. At basins with adequate records, frequency distributions are fitted to the time series of flood volumes to evaluate extreme volumes. Where records are inadequate, information at adjacent and/or similar sites is used in conjunction with available records to construct time series and estimate extreme volumes. If, on the other hand, the hydrograph shape for these extreme events is desired, unit hydrographs must be developed using available data. The shape of a unit hydrograph is defined by two time-related parameters, W_{50} and W_7. These are the widths (in hours) of the unit hydrograph at 50% and 75% of the peak discharge levels. These widths are sometimes regressed with basin characteristics in addition to the peak discharges to develop regionalized relationships of the form:

$$W_x = a\ (Q_p / A)^b$$

where

W is the hydrograph width, in hrs, corresponding to 'x' percentage of the peak discharge Q_p (in cfs), A is the drainage area (mi.^{2}), and a and b are constants.

Ungaged Sites: Flood volumes at ungaged watersheds are estimated in two ways. First, regional regression equations that relate flood volumes (estimated at gaged locations) to basin and/or hydro-climatic characteristics are extended to ungaged watersheds. Secondly, volume is estimated as the area under the simulated extreme runoff hydrograph. The principal drawback with the former approach is the lack of a duration component in the estimated volume. In other words, the approach gives a definite value for a 100-year flood volume but does not, for example, give any information about a 100 year-10 day flood volume. The Natural Environment Research Council developed an approach that relates volumes for different durations to the mean annual instantaneous flood. These ratios (called reduction ratios) are then plotted against durations to give reduction curves.

The other method uses synthetic long term rainfall runoff modeling to estimate the volumes for different durations. The largest runoff volume for each duration interval is determined for every water year, and a frequency distribution of these curves at each station is then calculated. Volume-duration-frequencies are then regionalized by multiple regression analysis using basin characteristics.

A technique commonly used to estimate extreme volumes is to develop peak-volume relationships of the form:

$$V = a(Q_p)^b$$

where V is the volume associated with a peak flow, Q_p, and a and b are constants. The exponent b usually has a value less than 1.

Volumes, V_T, for different recurrence intervals can thus be estimated from the corresponding peaks, Q_{PT} using the above equation and by assuming that the recurrence intervals of the volumes are the same as those of peaks. The antecedent rainfall, soil moisture and other hydro-climatic conditions must be known to validate this assumption. The estimated volumes of runoff may differ significantly from the actual volumes, however. The lack of agreement between measured and estimated volumes is primarily associated with inaccurate estimation of the exponent b.

An extension of the previous technique is to use peak-volume relationships that include basin and/or climatic characteristics. The relationship takes the form:

$V = a\,(Q_p)^b(S^c)(A^d)(I^e)$

Where V is the flood volume corresponding to a peak discharge of Q_p produced by a storm of intensity I. A is the area of the watershed with slope S, and a, b, c, d and e are constants.

Limitations

There exist several drawbacks with the techniques presented above. Linearity is usually assumed, as in the unit hydrograph theory, for mathematical simplicity yet runoff relations are decidedly nonlinear. Duration is not addressed in most peak-volume relationships currently in use. The volume under the hydrograph is a function of both the peak and duration. It is therefore possible to have flows of different volumes for the same peak. It is sometimes useful for design engineers to have a knowledge of the volumes of flow for specific durations rather than the total volume under the hydrograph (an example of such a requirement is determination of the time of inundation of vegetation used in bioengineering).

For gaged watersheds, it is possible to estimate partial volumes of flow by simulating runoff hydrographs for extreme peaks using a suitable calibrated model with available data. For ungaged watersheds, however, it is not possible to adopt the same approach since data are not available. Volumes of flow generated by multiple or non-independent events can rarely be reproduced without continuous simulation models. Also, stream flow data for severe storms are sometimes unavailable owing to technical problems such as malfunctioning of the gage or the gage being washed away. The latter is particularly true for small watersheds.

In all the approaches cited above, the assumption of the same recurrence interval for peaks and volumes is highly questionable. Volumes estimated using peaks of specific recurrence intervals are unlikely to reflect the true recurrence intervals of the volumes. For example, it is possible to have flows with smaller peaks producing larger volumes of flow by virtue of a larger timebase of the hydrograph. Such discrepancies can be attributed to variation in the rainfall pattern, difference in storm duration and/or direction of storm movement. The antecedent rainfall, soil moisture and other hydro-climatological conditions must also be known to validate this assumption. For example, convective storms common in Texas can produce very high peaks without high volumes.

In the absence of adequate peak discharge information, synthetic design storms are used in conjunction with rainfall-runoff models to generate long-term peaks. The assumption here is that the peak discharges have the same return period as the design storms. Volumes are then evaluated from the simulated hydrography. The drawback here is that it is unlikely for the rainfall, peak discharge and the runoff volume to all have the same frequency of occurrence.

Finally, the techniques described above are best suited to non-urban watersheds. Little work has been done to characterize necessary adjustments to these techniques to account for urbanization. Developing watersheds can also limit the applicability of gage data since the runoff characteristics of the watershed change with development. Therefore, it is important to assess the state of the watershed. Despite their drawbacks, the methods discussed above give the best possible estimates of flood volumes in the absence of actual measurements. There remains a need to develop methodologies that address, avoid or eliminate identified errors and omissions.

Flow Frequency

Seasonal variations of stream flow are somewhat predictable using statistical analyses of historical flow information. Flow frequency is the probability or percent chance of a given flow being exceeded in any given year, or as the average number of years between the given flows (Fig. 12). For example, a flow that has a 100-year recurrence interval is expected to be exceeded, on average, only once in any 100-year period. Another way of stating this is that, in any given year, a flood flow has a 1 percent chance or 0.01 probability of exceeding the 100-year flood. The exceedance probability, p, and the recurrence interval, T, are related by $T = 1/p$. It is useful to determine the flood frequency for peak values that might occur in the 1.5-, 5-, 10-, 50- and 100-year storm events to be aware of what potential flow events may occur. Note that the probability values for these events are 0.66, 0.20, 0.10, 0.02, and 0.01, respectively (or 66%, 20%, 10%, 2% and 1% chance of recurrence, respectively).

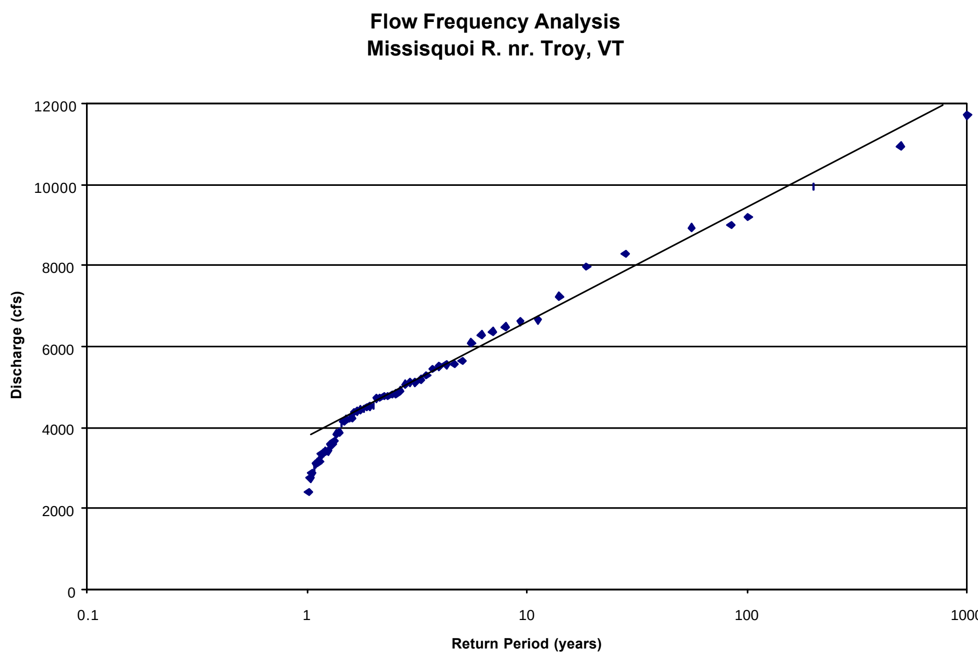


Figure 4.3 Flow frequency curve

Flood frequency estimates also may be generated using precipitation data and applicable watershed runoff models such as HEC-1, TR-20, and TR-55. The precipitation record for various return-period storm events is used by the watershed model to generate a runoff hydrograph and peak flow for that event. The modeled rainfall may be from historical data or from an assumed time distribution of precipitation (e.g., a 2-year, 24-hour rainfall event). This method of generating flood frequency estimates assumes the return period of the runoff event equals the return period of the precipitation event (e.g., a 2-year rainfall event will generate a 2-year peak flow). The validity of this assumption depends on antecedent moisture conditions, basin size, and a number of other factors. However, some of this error can be accounted for by calibrating the runoff model to a stream gage. In developing watersheds, event calibration may be necessary.

Hydrographs and Flow Duration Curves

The baseflow component of streamflow is important because it provides the channel with water in times of little or no precipitation. Stormflow, on the other hand, helps shape the channel, can induce floods, and transports materials to and from the channel.

A hydrograph is a tool used to show how discharge changes over time in response to a runoff event. It basically charts how long the stream takes to rise from baseflow to maximum discharge and then back to baseflow conditions. Urbanization or other changes within a watershed can affect the shape of the hydrograph, changing both the magnitude of peak discharge and reducing the time to peak following a rainfall event.

Flows may range from no flow in ephemeral streams to out-of-bank flood flows and all conditions in between. However, in addition to the elevation component of flow, or flow stage, a key hydraulic characteristic of concern in designing stream corridor restoration is the length of time certain flows occur, or flow duration. These two factors allow consideration of the cross-sectional area with both discharge (volume over time) and duration (length of time for a given discharge). The duration and season during which these flows occur is also important to the restoration design, due to their potential effects on aquatic and riparian biota and vegetation.

The amount of time that certain flow levels exist in the stream usually is represented by a flow duration curve depicting the percent of time a given streamflow was equaled or exceeded over a given period. Flow duration curves usually are based on daily streamflow (a record containing the average flow for each day) and describe the flow characteristics of a stream throughout a range of discharges without regard to the sequence of occurrence. The construction of flow duration curves is accomplished by defining the cumulative histogram of streamflow by using 20 or more well-distributed class intervals of streamflow data.

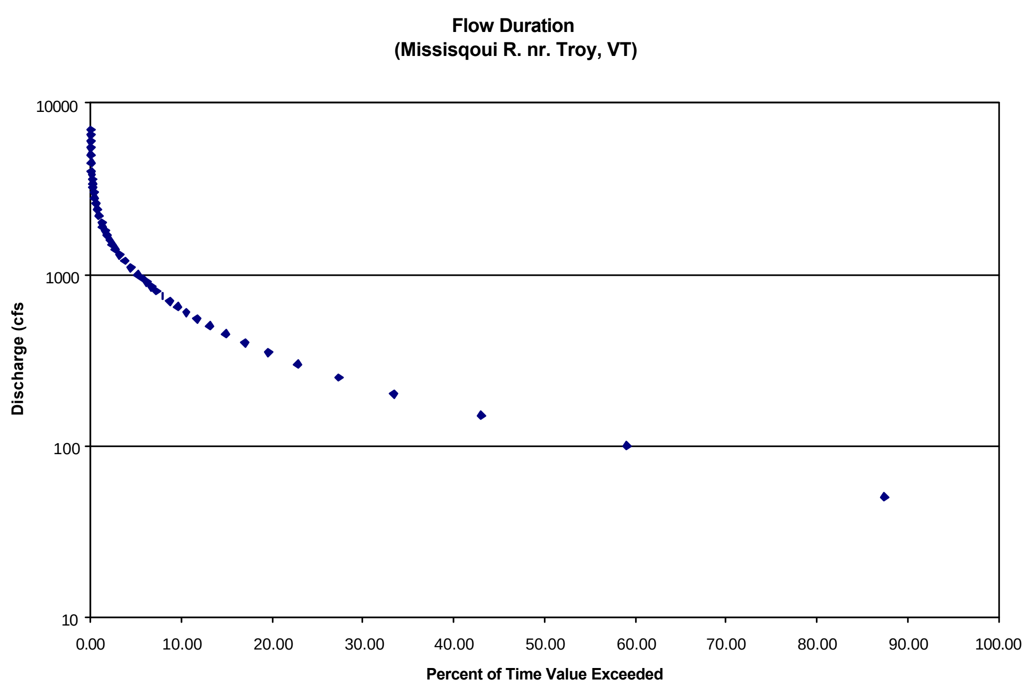


Figure 4.4 Flow duration curve

Estimating flow duration characteristics at ungauged sites usually is attempted by adjusting data from a nearby stream gauge in a hydrologically similar basin. Flow duration characteristics from the stream gauge record are expressed per unit area of drainage basin at the gauge (i.e., in cfs/sq mi) and are multiplied by the drainage area of the ungauged site to estimate flow duration characteristics there. The accuracy of such a procedure is directly related to the similarity of the two sites. Generally, the drainage area at the stream gauge and ungauged sites should be fairly similar, and streamflow characteristics should be similar for both sites. Additionally, mean basin elevation and physiography should be similar for both sites. Such a procedure does not work well and should not be attempted in stream systems dominated by local convective storm runoff or where land uses vary significantly between the gauged and ungauged basins.

Guidelines for determining the frequency of floods at a particular location using streamflow records are documented by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (IACWD 1982, Bulletin 17B). The guidelines described in Bulletin 17B are used by all federal agencies in planning activities involving water and related land resources. Bulletin 17B recommends fitting the Pearson Type III frequency distribution to the logarithms of the annual peak flows using sample statistics (mean, standard deviation, and skew) to estimate the distribution parameters. Procedures for outlier detection and adjustment, adjustment for historical data, development of generalized skew, and weighting of station and generalized skews are provided. The station skew is computed from the observed peak flows, and the generalized skew is a regional estimate determined from estimates at several long-term stations in the region. The U.S. Army Corps of Engineers also has produced a user's manual for flood frequency analysis (Report CPD-13 1994) that can aid in determining flood frequency distribution parameters.

Guidelines for low-flow frequency analysis are not as standardized as those for flood frequency analysis. No single frequency distribution or curve-fitting method has been generally accepted. Data used in low-flow frequency analyses are typically the annual minimum average flow for a specified number of consecutive days. The 7-day, 10-year low flow, or Q7,10, is used by about half of the regulatory agencies in the United States for managing water quality in receiving waters. The USGS and U.S. EPA recommend using the Pearson Type III distribution to the logarithms of annual minimum d-day low flows to obtain the flow with a nonexceedance probability p (or recurrence interval T = 1/p). The Pearson Type III low-flow estimates are computed from the equation:

$$X_{d,T} = M_d - KS_d$$

where:
$X_{d,T}$ = the logarithm of the annual minimum d-day low flow for which the flow is not exceeded in 1 of T years or which has a probability of p = 1/T of not being exceeded in any given year
M_d = the mean of the logarithms of annual minimum d-day low flows
S_d = the standard deviation of the logarithms of the annual minimum d-day low flows
K = the Pearson Type III frequency factor.

The desired quantile, Qd,T, can be obtained by taking the antilogarithm of the equation. If the computed Pearson Type III curve is significantly different from the Weibull plotting positions, the computed curve is adjusted to be consistent with the plotting positions.

Constructing a Specific Gage

Perhaps one of the most useful tools available to the river engineer or geomorphologist for assessing the historical stability of a river system is the specific gage record. A specific gage record is a graph of stage for a specific discharge at a particular gaging location plotted against time. A channel is considered to be in equilibrium if the specific gage record shows no consistent increasing or decreasing trends over time, while an increasing or decreasing trend is indicative of an aggradational or degradational condition, respectively.

The first step in a specific gage analysis is to establish the stage vs. discharge relationship at the gage for the period of record being analyzed. A rating curve is developed for each year in the period of record. A regression curve is then fitted to the data and plotted on the scatter plot. Once the rating curves have been developed, the discharges to be used in the specific gage record must be selected. This selection will depend largely on the objectives of the study. It is usually advisable to select discharges that encompass the entire range of observed flows. A plot is then developed showing the stage for the given flow plotted against time.

Specific gage records are an excellent tool for assessing the historical stability at a specific location. However, specific gage records only indicate the conditions in the vicinity of the particular gaging station and do not necessarily reflect river response farther upstream or downstream of the gage. Therefore, even though the specific gage record is one of the most valuable tools used by river engineers, it should be coupled with other assessment techniques in order to assess reach conditions, or to make predictions about the ultimate response on a river.

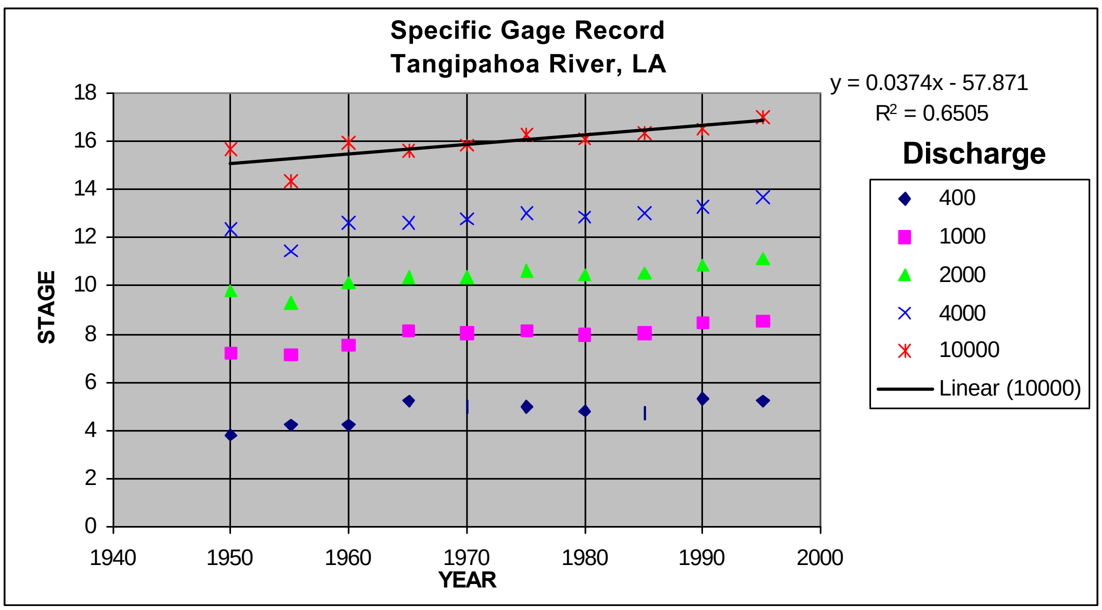


Figure 4.5 Example specific gage

Flow Routing

Although quite adequate for most rivers, this empirical rating curve is single-valued (i.e., one-to-one relationship between h and Q) and may not reflect the hydraulic conditions in the river system (e.g., backwater due to very mild river bottom slopes (<0.005%)). In such rivers, the water-surface elevation tends to be higher on the falling limb of the hydrograph than on the rising limb at the same discharge producing a "looped" rating curve. The band-width of the loop can range from a few centimeters to several meters depending on the hydraulic conditions (i.e., primarily, the slope of the river profile and the rate of rise of the hydrograph). The magnitude of the loop increases as the slope decreases and as the rate of rise increases. Usually a single-valued rating curve is drawn through the loop producing an average error of half the band-width of the loop. Other rating changes (shifts) or erratic loops are caused by tributary inflow, natural channel constrictions, or man-made constrictions (e.g., dams, bridges), and by sand/gravel river bed changes due to sediment transport effects.

It may be necessary to use an unsteady flow, dynamic, hydraulic routing model which determines the water-surface elevation (h) and discharge (Q) at specified locations along the length (x) of the waterway (river, reservoir, etc) when subjected to an unsteady flow event such as a flood wave or dam-break wave. These models are generally based on an implicit finite-difference solution of the complete one dimensional Saint-Venant unsteady flow equations coupled with an assortment of internal boundary conditions representing unsteady flows controlled by a wide spectrum of hydraulic structures.

Hydraulic Assessments

Uniform Flow

Under conditions of constant width, depth, area, and velocity, the water surface slope and energy grade line approach the slope of the streambed, producing a condition known as "uniform flow." One feature of uniform flow is that the streamlines (the traces of the path that a particle of water would follow in the flow) are parallel and straight. Perfectly uniform flow is rarely realized in natural channels, but the condition is approached in some reaches where the geometry of the channel cross section is relatively constant throughout the reach.

Conditions that tend to disrupt uniform flow include bends in the stream course; changes in cross-section geometry; obstructions to flow caused by large roughness elements, such as channel bars, large boulders, and woody debris; or other features that cause convergence, divergence, acceleration, or deceleration of flow. Resistance equations also may be used to evaluate these nonuniform flow conditions (gradually varied flow); however, energy-transition considerations (backwater calculations) must then be factored into the analysis. This requires the use of multiple transect models (e.g., WSP2 and HEC-2; HEC2 is a water surface profile computer program developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center in Davis, CA; WSP2 is a similar program developed by the USDA Natural Resources Conservation Service.)

Backwater Effects

Straight channel reaches with perfectly uniform flow are rare in nature and, in most cases, may only be approached to varying degrees. If a reach with constant cross-sectional area and shape is not available, a slightly contracting reach is acceptable, provided that there is no significant backwater effect from the constriction. Backwater occurs where the stage-discharge relationship is controlled by the geometry downstream of the area of interest (section control). Manning's equation assumes uniform flow conditions.. Manning's equation used with a single cross section, therefore, will not produce an accurate stage-discharge relationship in pools or other backwater areas. In addition, expanding reaches also should be avoided, as there are additional energy losses associated with channel expansions. When no channel reaches are available that meet or approach the condition of uniform flow, it may be necessary to use multi-transect models (e.g., HEC-2) to analyze cross-section hydraulics. If there are elevation restrictions corresponding to given flows (e.g., flood control requirements) the water surface profile for the entire reach is needed and use of a multi-transect (backwater) model is required.

Standard Step Backwater Computation

Many computer programs (e.g., HEC-2, HEC-RAS) are available to compute water surface profiles, but the computational procedure lends itself to formulation in a spreadsheet as well. The standard step method of Chow (1959, p. 265) can be used to determine the water surface elevation (depth) at the upstream end of the reach by iterative approximations. This method uses trial water surface elevations to determine the elevation that satisfies the energy and friction equations written for the end sections of the reach. In using this method, cross sections should be selected so that velocities are increasing or decreasing continuously throughout the reach.

Sedimentation

The amount and type of sediment supplied to a stream channel is an important consideration in restoration, because sediment is part of the balance (i.e., between energy and material load) that determines channel stability. A general lack of sediment relative to the amount of stream power, shear stress, or energy in the flow (indexes of transport capacity) usually results in sediment being eroded from the channel boundary of an alluvial channel. Conversely, an oversupply of sediment relative to the transport capacity of the flow usually results in sediment being deposited in that reach of stream.

Bed material load sediment transport analyses are required whenever a restoration project involves reconstructing a length of stream exceeding two meander wavelengths. A reconstruction that modifies the size of a cross section and the sinuosity for such a length of channel should be analyzed to ensure upstream sediment loads can be transported through the reconstructed reach with minimal deposition or erosion. Different storm events and the average annual bed material load transport quantities also should be examined.

Three primary geomorphic processes are involved in sedimentation:

- Erosion—the detachment of soil particles.
- Transport—the movement of eroded soil particles in flowing water;.
- Deposition—eroded soil particles settle to the bottom of a water body or are left behind as water leaves. Sediment deposition can be transitory, as in a stream channel from one storm to another, or more or less permanent, as in a larger reservoir.

Each of these processes are important to the function and stability of a stream restoration or stabilization project and efforts to quantify sedimentation are generally warranted.

Bed Material Particle Size Distribution

Many of the analyses associated with restoration projects require an evaluation of the particle-size distribution of the bed material of the stream. For streams with no significant channel armor and bed material finer than medium gravel, bed material samplers developed by the Federal Interagency Sedimentation Project (FISP 1986) may be used to obtain a representative sample of the streambed, which is then passed through a set of standard sieves to determine percent-by-weight of particles of various sizes. The cumulative percent of material finer than a given size then may be determined.

Particle-size data are usually reported in terms of d_i, where i represents some nominal percentile of the distribution, and d_i represents the particle size, usually expressed in millimeters, at which i percent of the total sample by weight is finer. For example, 84 percent of the total sample would be finer than the d_{84} particle size (see Figure 4.6).

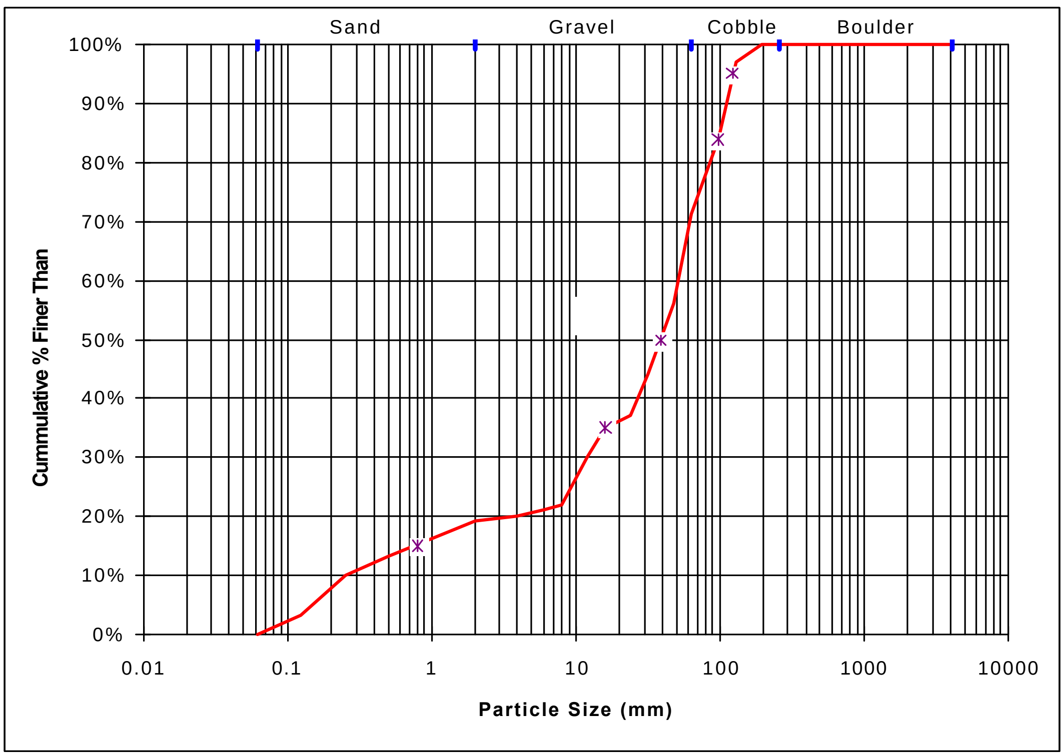


Figure 4.6 Sediment gradation curve

In steep mountain rivers with substrate much coarser than the medium-gravel limitation of FISP samplers, a pebble count, in which at least 100 bed-material particles are manually collected from the streambed and measured, is used to measure surface particle size (Wolman 1954). At each sample point along a cross section, a particle is retrieved from the bed, and the intermediate axis (not the longest or shortest axis) is measured. The measurements are tabulated as to number of particles occurring within predetermined size intervals, and the percentage of the total number in each interval then is determined. Again, the percentage in each interval is accumulated to give a particle-size distribution, and the particle-size data are reported as described above.

Bed Stability

In unstable channels, the relationship between bed elevation and time (years) can be described by nonlinear functions, where change in response to a disturbance occurs rapidly at first and then slows and becomes asymptotic with time. Plotting of bed elevations against time thus permits evaluating bed-level adjustment and indicates whether a major phase of channel incision has passed or is ongoing. Various mathematical forms of this function have been used to characterize bed-level adjustment at a site and to predict future bed elevations. This method also can provide valuable information on trends of channel stability at gauged locations where abundant data from discharge measurements are available.

Two mathematical functions have been used to describe bed level adjustments with time. The first is a power function (Simon 1989):

$$E = a\ tb$$

where E = elevation of the channel bed, in feet; a = coefficient, determined by regression, representing the premodified elevation of the channel bed, in feet; t = time since beginning of adjustment process, in years, where t0 = 1.0 (year prior to onset of the adjustment process); and b = dimensionless exponent, determined by regression, and indicative of the nonlinear rate of channel-bed change (negative for degradation and positive for aggradation).

The second is a dimensionless form of an exponential equation (Simon 1992):

$$z / z_0 = a + b \exp(- k\ t)$$

where z = the elevation of the channel bed (at time t); z_0 = the elevation of the channel bed at t_0; a = the dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z/z_0) when the equation becomes asymptotic, a>1 = aggradation, a<1 = degradation; b = the dimensionless coefficient, determined by regression and equal to the total change in the dimensionless elevation (z/z_0) when the equation becomes asymptotic; k = the coefficient determined by regression, indicative of the rate of change on the channel bed per unit time; and t = the time since the year prior to the onset of the adjustment process, in years (t_0=0).

Future elevations of the channel bed can, therefore, be estimated by fitting the equations to bed elevations and by solving for the period of interest. Either equation provides acceptable results, depending on the statistical significance of the fitted relation. Statistical significance of the fitted curves improves with additional data. Degradation and aggradation curves for the same site are fit separately. For degrading sites, the equations will provide projected minimum channel elevations when the value of t becomes large and, by subtracting this result from the floodplain elevation, projected maximum bank heights. A range of bed-adjustment trends can be estimated by using different starting dates in the equations when the initial timing of bed-level change is unknown. Use of the equations, however, may be limited in some areas because of a lack of survey data.

Once the minimum bed elevation has been obtained, that elevation can be substituted back into the equation used as the new starting elevation at a t_0 for the secondary aggradation phase that occurs during channel widening (see discussion of channel evolution above). Secondary aggradation occurs at a site after degradation reduces channel gradient and stream power to such an extent that sediment loads delivered from degrading reaches upstream can no longer be transported. The a or b values for Simon's power function for estimating secondary aggradation can be obtained either from interpolating existing data or from estimating its value as about 60 percent less than the corresponding value obtained for the degradation phase.

The variation of the regression coefficients a and b with longitudinal distance along the channel can be used as an empirical model of bed-level adjustment providing there are data from enough sites to establish a relation with distance along the channel or river system. Estimates of bed-level change with time for unsurveyed sites can be obtained using interpolated coefficient "a" values and t_0. For channels downstream from dams, the shape of the "a"-value curve would be similar but inverted; maximum amounts of degradation (minimum a values) occur immediately downstream of the dam and attenuate nonlinearly with distance further downstream.

Numerical analyses and models, such as HEC-6, are also used to predict aggradation and degradation (incision) in stream channels. HEC-6 is a one-dimensional moveable boundary open channel flow numerical model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods, typically years, although applications to single flood events are possible. A continuous discharge record is partitioned into a series of steady flows of variable discharge and duration. For each discharge, a water surface profile is calculated, providing energy slope, velocity, depth, and other variables at each cross section. Potential sediment transport rates are then computed at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each reach. The amount of scour or deposition at each section is then computed and the cross section geometry is adjusted for the changing sediment volume. Computations then proceed to the next flow in the sequence and the cycle is repeated using the updated cross section geometry. Sediment calculations are performed by grain size fractions, allowing the simulation of hydraulic sorting and armoring.

Sediment Discharge Functions

The selection of an appropriate discharge formula is an important consideration when attempting to predict sediment discharge in streams. Numerous sediment discharge formulas have been proposed, and a specific formula may be more accurate than others when applied to a particular river, but it many not be accurate for other rivers. Selection of a sediment transport formula should include the following considerations (modified from Yang 1996):

- Type of field data available or measurable within time, budget, and work hour limitations
- Independent variables that can be determined from available data
- Limitations of formulas versus field conditions

If more than one formula can be used, the rate of sediment discharge should be calculated using each formula. The formulas that best agree with available measured sediment discharges should be used to estimate the rate of sediment discharge during flow conditions when actual measurements are not available. The following formulas may be considered in the absence of any measured sediment discharges for comparison:

- Meyer-Peter and Muller (1948) formula when the bed material is coarser than 5 mm
- Einstein (1950) formula when bed load is a substantial part of the total-sediment discharge
- Toffaleti (1968) formula for large sand-bed rivers
- Colby (1964) formula for rivers with depths less than 10 feet and median bed-material values less than 0.8 mm
- Yang (1973) formula for medium to coarse sand-bed rivers
- Yang (1984) formula for gravel transport when most of the bed material ranges from 2 to 10 mm
- Ackers and White (1973) or Engelund and Hansen (1967) formula for sand bed streams having subcritical flow
- Laursen (1958) formula for shallow rivers with fine sand or coarse silt

Available sediment data from a gaging station may be used to develop an empirical sediment discharge curve in the absence of a satisfactory sediment discharge formula, or to verify the sediment discharge trend from a selected formula. Measured sediment discharge or concentration should be plotted against streamflow, velocity, slope, depth, shear stress, stream power, or unit stream power. The curve with the least scatter and systematic deviation should be selected as the sediment rating curve for the station.

Slope Stability

The physical properties of bank materials should be described to aid characterization of potential stability problems and identification of dominant mechanisms of bank instability. The level of intensity of geotechnical investigations varies in planning and design. During planning, enough information must be collected to determine the feasibility of alternatives being considered. For example, qualitative descriptions of bank stratigraphy obtained during planning may be all that is required for identifying dominant modes of failure in a study reach. Thorne (1992) describes stream reconnaissance procedures particularly for recording streambank data.

Qualitative Assessment of Bank Stability

Visual assessments of streambanks before, during and after runoff events usually provide significant evidence of the overall stability of the banks. In addition to identifying the mechanisms of failure as described in Chapter 3, a qualitative assessment of the banks should be conducted to ascertain their overall stability. Natural streambanks frequently are composed of distinct layers reflecting the depositional history of the bank materials. Each individual sediment layer may have physical properties quite different from other layers. The bank profile therefore will respond according to the physical properties of each layer. Since the stability of streambanks with respect to geotechnical failures depends on the geometry of the bank profile and the physical properties of the bank materials, dominant failure mechanisms tend to be closely associated with characteristic stratigraphy or succession of layers.

Shear Strength Analyses

Quantitative analysis of bank instabilities is considered in terms of force and resistance. The shear strength of the bank material represents the resistance of the boundary to erosion by gravity. Shear strength is composed of cohesive strength and frictional strength. For the case of a planar failure of unit length, the Coulomb equation is applicable

$$Sr = c + (N - \&) \tan f$$

where Sr = shear strength, in pounds per square foot, c = cohesion, in pounds per square foot; N = normal stress, in pounds per square foot; & = pore pressure, in pounds per square foot; and f = friction angle, in degrees.

Also:

$$N = W \cos q$$

where W = weight of the failure block, in pounds per square foot; and q = angle of the failure plane, in degrees.

The gravitational force acting on the bank is:

$$Sa = W \sin q$$

Factors that decrease the erosional resistance (Sr) such as excess pore pressure from saturation and the development of vertical tension cracks favor bank instabilities. Similarly, increases in bank height (due to channel incision) and bank angle (due to undercutting) favor bank failure by increasing the gravitational force component. In contrast, vegetated banks generally are drier and provide improved bank drainage, which enhances bank stability. Plant roots provide tensile strength to the soil, which is generally strong in compression, resulting in reinforced earth that resists mass failure, at least to the depth of roots.

Predictions of Bank Stability

No algorithms or techniques exist that allow the prediction of precise location, time, or extent of future bank erosion. However, if conditions at a site are unchanged over an extended period, general bank stability in the future can be inferred from the past. In addition, some analytical techniques can be useful to determine the following:

- The general timing of the initiation of general bank instabilities (in the case of degradation and increasing bank heights)
- The general timing of renewed bank stability (in the case of aggradation and decreasing bank heights)
- The bank height and angle that need to be engineered to attain a stable bank configuration under a range of moisture conditions.

Estimates of future channel widening also can be made using measured channel-width data over a period of years and then fitting a nonlinear function to the data. Williams and Wolman (1984) used a dimensionless hyperbolic function of the following form to estimate channel widening downstream from dams:

$$(W1 / Wt) = j1 + j2 (1 / t)$$

Where:

$W1$ = initial channel width, in feet;

Wt = channel width at t years after $W1$, in feet;

t = time, in years;

$j1$ = intercept; and

$j2$ = slope of the fitted straight line on a plot of $W1 / Wt$ versus $1/t$.

Habitat Quantification

Habitat character and quality affect the abundance, size, health, and composition of aquatic species such as fish. Poorly defined goals lead to widespread problems with inadequate, improper, and inaccurate fish habitat information. Habitat analysis is a process that requires (1) identifying problems, (2) defining objectives, (3) setting goals, (4) implementing actions to address problems, and (5) evaluating actions to determine if objectives have been achieved. Habitat analyses are undertaken for a variety of reasons including:

- Improved understanding of basic species requirements
- Inventorying to establish baseline information
- Quantifying habitat quality
- Determining anthropogenic impacts
- Monitoring effects of habitat improvement activities

Regardless of the type of habitat analyses, certain sampling principles must be followed. Standardized sampling protocols are required to describe temporal trends and techniques must be repeatable and be sufficiently accurate and precise to detect changes. Terms and units of measure, sampling methods, criteria for evaluation, spatial and temporal scales, stratification and classification systems, and data storage and analysis should all be standardized.

Inventorying to Establish Baseline Information

One reason for conducting a habitat analysis might be to describe baseline conditions. The U.S. Forest Service developed an inventory technique that is applied basinwide (Hankin and Reeves 1988). Interpreting data from inventories is frequently difficult because sampling techniques often are imprecise; the data give little insight into the habitat features that may affect fish; and the spatial and temporal dimensions of the data often are incongruent or not easily depicted. Vast amounts of inventory data are gathered and/or stored with little understanding as to how they may be used by resource managers, especially by fisheries managers.

Quantifying Habitat Quality

Analyzing habitat features that limit fish production is a challenge to fisheries managers. Limiting factors can be anything that impedes the dynamics of an organism or population. They also can be defined as the critical minimum requirements for survival. Such analyses include observation and interpretation of the habitat features that are affecting fish survival. Hunter (1991) stated that when a manager finds an attribute that does not meet a fish's minimum requirements, a limiting factor is identified. Fisheries managers want to identify limiting factors and relieve them to enhance fish production and achieve the production potential, ecological capability, or optimum productivity of a system.

However, few habitat analysis tools focus on identifying limiting factors or the relations between habitat and production potential. Such analytical approaches need to go beyond identifying the life stage or habitat feature that may limit production, and instead reveal the root cause of the problem. Sampling through the year or throughout a watershed may be necessary. As fisheries managers, we have barely begun to develop analytical tools that can identify limiting factors and specific habitat improvement needs. Much of the sampling and many of the analyses provide data that do not or cannot identify limiting factors. When this happens, the effort becomes little more than a form of occupational therapy, the activity trap.

Habitat Value

A system has been developed to simulate the physical habitat as a function of streamflow: the Physical HABitat SIMulation system (PHABSIM), described in Milhous et al. (1989). If PHABSIM is used to generate the habitat-versus-streamflow function, then the physical habitat is called Weighted Usable Area and **PH( ) = WUA( )**, where **WUA( )** is the weighted usable area versus streamflow function. The physical habitat represents the space in a river that can be used as habitat by a given species and life stage of fish. The concept advanced by Milhous (1983) is that a physical habitat-versus-streamflow function can be used as a surrogate for an economic production function. In treating the physical habitat-versus-streamflow function as surrogate production function, the assumption is made that the value of the instream flows is proportional to the habitat produced by the flows. As with other economic benefits, it is desirable to know the time series of the benefits produced.

The premise of time series analysis is that the instream physical habitat at a given time and place can be calculated as a function of the streamflow using the equation

$$\mathbf{HA}(t) = \mathbf{PH}(\mathbf{Q}(t))$$

where **PH( )** is the physical habitat-versus-streamflow function for a given life stage and species of aquatic organism or river activity; **Q (*t*)** is the streamflow at time ***t***; and **HA(*t*)** is the habitat area for time ***t***.

Time series requires two types of data--streamflow data and the habitat-versus-streamflow function. The streamflow time series is used to develop a physical habitat time series.

Water Quality

Significant Parameters

There are hundreds of chemical compounds that can be used to describe water quality. It is typically too expensive and too time-consuming to analyze every possible chemical of interest in a given system. In addition to selecting a particular constituent to sample, the analytical techniques used to determine the constituent also must be considered, as should the chemistry of the constituent. Whether the chemical is typically in the dissolved state or sorbed onto sediment makes a profound difference on the methods used for sampling and analysis, as well as the associated costs, for example.

Often it is effective to use parameters that integrate or serve as indicators for a number of other variables. For instance, dissolved oxygen and temperature measurements integrate the net impact of many physical and chemical processes on a stream system, while soluble reactive phosphorus concentration is often taken as a readily available indicator of the potential for growth of periphytic algae.

Collecting and Presenting Data

Key documents describing methods of water sample collection for chemical analysis are the U.S. Geological Survey (USGS) protocol for collecting and processing surface water samples for determining inorganic constituents in filtered water (Horowitz et al. 1994), the field guide for collecting and processing stream water samples for the national water quality assessment program (Shelton 1994), and the field guide for collecting and processing samples of stream bed sediment for analyzing trace elements and organic contaminants for the national water quality assessment program (Shelton and Capel 1994). A standard reference document describing methods of sediment collection is the US TWRI, Field Methods for Measurement of Fluvial Sediment (Guy and Norman 1982). The USGS is preparing a national field manual, describing techniques for collecting and processing water quality samples (Franceska Wilde, personal communication, 1997).

The needed frequency of sampling depends on both the constituent of interest and management objectives. In general, water quality constituents that are highly variable in space or time require more frequent monitoring to be adequately characterized. Field sampling and water quality analyses are time-consuming and expensive, and schedule and budget constraints often determine the frequency of data collection. Such constraints make it even more important to design data collection efforts that maximize the value of the information obtained. Statistical tools often are used to help determine the sampling frequency and the relative merits of options such as simple random sampling, stratified random sampling, two-stage sampling, and systematic sampling.

Most samples represent a point in space and provide direct information only on what is happening at that point. A key objective of site selection is to choose a site that gives information that is representative of conditions throughout a particular reach of stream. Although most hydrologic systems are very complex, it is essential to have a fundamental understanding of the area of interest to make this determination. Practical considerations are also an important part of sample collection. Sites must be accessible, preferably under a full range of potential flow and weather conditions and water quality sample sites should coincide with locations at which flow can be accurately gauged. For this reason, sampling often is conducted at bridge crossings, taking into consideration the degree to which artificial channels at bridge crossings may influence sample results.

5 Soil BioEngineering

Chapter Overview

Streambank erosion is a natural process that occurs in all fluvial systems, typically on large time scales. Streambank erosion can also be induced or exaggerated by human activities. Numerous factors within the watershed can contribute to anthropogenic streambank erosion in a given location. Three major causes of accelerated erosion related to human activity are channel modification, reservoir construction, and land use changes (Figure 5.1). The more stream management problems are addressed in the context of an entire watershed using a systems approach, and the better we are able to understand and accomodate natural stream processes, the more successful our efforts will be. A systems approach involves efforts to identify and address all significant contributing factors in addition to treating the immediate symptom, bank erosion. It also means using system-compatible bank stabilization techniques. Soil bioengineering techniques often fulfil this need. This chapter presents a number of soil bioengineering techniques that can be combined and modified to suit a wide variety of streambank and channel restoration needs.

NOTE: Figures are presented at the end of the chapter.

System Elements

Generally speaking, bioengineering is considered "a soft fix." This is not necessarily the case. On first or second order streams, the sole use of vegetation with perhaps a little wire and a few stakes for holding the vegetation until it is established makes bioengineering more of a soft treatment. However, bioengineering is used also in combination with hard structures. These hard structures are used to protect the toe of the bank from under cutting and the flanks (ends of treatment) from eroding. The larger the stream or stronger the flow, the more probable that hard structures will be incorporated into the bioengineering design model. This is also true when risks become greater, such as when an expensive facility is being threatened. As an example, a utility tower along a stream in Georgia[1] was being threatened by erosion. A rock revetment had previously been used in front of the tower, but was washed out. A bioengineering treatment that incorporated live willow whips and a log crib were installed to control erosion. Crib logs controlled undercutting and flanking while the live willow whips installed between the log stringers developed and strengthened the overall structure and gave it a "green" appearance.

In most bioengineering references, hard structures such as rock riprap, log/tree revetments, tree butts, and deflection dikes were used to protect toes from being undercut or flanks at the upper and lower ends from being washed out. In these cases, water currents are prevented from undercutting the bank either through direct protection of the lower bank with some hard structure or material or through some kind of deflection structure that deflects the currents off of the bank. Deflection structures may be some kind of spur dike, vane, transverse dike, or bendway weir. Figure 5.2 shows two timber cribs serving as deflection structures on the upper Missouri River to direct current away from the bank. In the case of hard toes on the lower bank, plants and engineered materials to hold them in place are positioned above the hard toe. Rock riprap keyed into the bank at both the upper and lower ends of a bioengineering treatment are called refusals (Figure 5.3) and prevent currents getting behind the structure, called flanking. In the case of a deflection structure, these are usually placed in a series at critical points of scour and plants with engineered materials are placed in between them to help hold the bank. With the aid of these structures and time, the planted vegetation establishes roots and stems in the bank to hold it together and trap sediment. This sedimentation, in turn, leads to spread of the planted species and colonization by other opportunistic plants.

Conventional Erosion Control Techniques

Hard protection is often thought of as being *traditional or conventional,* although in fact vegetative protection pre-dates the use of most conventional hard materials by centuries. The range of materials and techniques available is well established, although use of some approaches is increasingly limited by their adverse environmental and aesthetic impacts.

Hard engineering is the option of-last resort, to be used when erosion prevention has failed and solutions based on active bank management or softer protection have been demonstrated by bank assessment to be either inadequate or inappropriate. This may of course be quite frequently the case, and it must be accepted that in many situations there is no realistic alternative to hard protection.

Generally, conventional solutions can be grouped into four broad categories based upon function:

1) structures whose primary function is to prevent erosion by armoring the eroding bank,

2) structures that prevent erosion by deflecting the current away from the bank;

3) methods that reduce the erosive capability within the channel; and

4) geotechnical methods of slope stabilization

Armoring Techniques

The armoring technique is the placement of a protective covering, usually consisting of stone, over part or all of the stream bank. Armoring techniques function by preventing the boundary shear induced by flowing water from contacting erodible bank material. These techniques affect the bank sediment input, roughness, and local shear. Material type and channel alignment determine the extent of the impacts. In general, armor structures cause a scour hole to develop at the toe of the structure and extend riverward for a limited distance.

The depth of scour varies with alignment and material type. Velocity may increase in the scour region, but there is little or no change in the velocity at points further riverward. If the structure does not encroach appreciably on the channel, there should be no measurable change in river stage for a given discharge. Bed sediment movement may be affected. Properly constructed armor structures, particularly if they incorporate a vegetation component, provide a locally diverse aquatic environment without significant effect on the hydraulic conditions of the adjacent river reaches. Riparian disruption is generally the greatest environmental concern, and measures should be taken to minimize impacts.

Stone-Fill Revetments - Stone-fill revetments are perhaps the most common of all streambank protection structures. Included within this group are several variations of the general theme of placing quarried stone, broken concrete, cobble, or soil cement parallel to the eroding bankline. The stone may be placed in a toe section with or without upper bank protection. A thin blanket may be used to armor the entire bank. The revetment may be windrowed, and allowed to launch as erosion undermines the structure. Revetments are often used in conjunction with other bank protection devices. A stone toe section with revegetation of the upper bank is one of the most cost effective solutions to most erosion problems (Figure 5.4). Revetments are very successful in stopping erosion on streams where the major problem is bank undercutting from toe erosion or general erosion of the bank by shear velocities of the river. They provide only a limited amount of protection against erosion on streams subject to headcuts or general bed degradation. Revetments must be properly designed and constructed with suitable material to be effective.

Soil-Covered Riprap - In urban areas or highly visible locations where it is advisable to keep banks mowed for aesthetic or safety purposes, riprap may be covered with soil and seeded to accelerate this process. This may also be done in areas where mowing is desired. Benefits of covering riprap with soil and seeding grass are largely aesthetic. Although access to the stream is improved, few aquatic or riparian habitat values are derived. Edaphic and climatic conditions are the major constraints to covering riprap with soil and seeding with vegetation, particularly grass. Covering riprap with soil and seeding is feasible only if climatic conditions are conducive to the growth of the plants or supplemental irrigation is practical. The practice has largely been confined to urban areas where aesthetics is a consideration, and where machine-mowing can replace more expensive hand-mowing maintenance methods. Soil covered riprap seeded with grass performs well in situations where flow velocities in the vicinity of the bank do not exceed 4 to 6 ft/s. Critical velocities vary with the variety of grass used and soil conditions.

Cellular Blocks - Cellular blocks are designed to be placed on a prepared bank in a manner that leaves many openings. This method allows vegetation to grow from cavities in precast concrete blocks. Construction often involves the placement of a filter cloth between the soil and the cellular blocks if the soil is erodible. Specialized equipment can be used to install the blocks but hand placement will be required when bank access is inadequate. Vegetation can then be planted or allowed to invade naturally. Cellular blocks have been successfully used in stream flow up to 15 feet per second. The holes in the blocks limit the potential of failure due to hydrostatic pressure, but turbulence may dislodge the blocks if they are not properly placed. Like riprap, cellular block conform to minor changes in the bank. However, it is not an economical alternative to riprap.

Geogrid - Non-woven polyester fabric shaped as hexagons, with sides approximately 8 inches and a depth of 4 to 8 inches, are stapled together to form a mat to the shape and area of the bank to be protected. The geogrid mat then is placed on the bank and filled with soil, sand, aggregate, or other native materials. The raised edges of the geogrid material provide the erosion protection until the vegetation becomes established within the cells. The geogrid provides virtually permanent erosion control due to the rot-proof nature of the materials used and the eventual establishment of vegetation which further enhances its structural integrity. Geogrid revetments are inexpensive, quick and easy to build. Turbulent flows at the toe of the geogrid is the most frequent cause of revetment failure. For this reason, it should usually be coupled with a low stone toe structure. Flanking is also a problem, so stone refusals at the upstream and downstream limits of the geogrid are recommended.

Gabions - Gabions are rock-filled wire or synthetic baskets that are wired together to form continuous structures. The mesh is typically galvanized or coated with polyvinyl chloride to reduce corrosion. Gabions can use lower quality stone than riprap structures and can be placed on steeper slopes. Gabion structures are flexible enough not to be vulnerable to minor bank shifts but need to be placed on a firm foundation. Gabions may also be used to construct deflective structures, and would have the same impacts as jetties or hardpoints when constructed as such. Sediment is usually deposited among the rocks in gabion structures, and vegetation often becomes established so that the structure is obscured and the stream has a natural appearance. Unvegetated gabions are similar in appearance to masonry work, which may be visually pleasing in some settings. The steep slopes on which gabions are sometimes placed may hinder wildlife access (Figure 5.5). Gabion structures can be designed with artificial overhangs, flow deflectors, and other features to enhance fish habitat. Failed baskets may be hazardous to recreationists, especially canoeists. Gabions have been widely used for streambank protection on streams located in a variety of environments in the US and Europe. They are most frequently used in urban areas, particularly on small watersheds where high flood conveyance is desired. Gabion streambank protection structures have performed very well in some settings. The major problem is basket failure, a problem that is aggravated by ice and other debris, gravel bedload movement, vandalism, and corrosive streamflows. Gabions are usually cost prohibitive when compared to riprap structures, but instances may occur when they are a preferred alternative.

Geotextile fabrics - On small streams, a good vegetative cover of grass or shrubs may be sufficient to protect streambanks from scour. But if the soils consist of easily erodible material such as sand or gravel, it is often necessary to provide temporary cover until the vegetation has become established. Various natural and synthetic fibers have been developed for use in erosion prevention. Many different applications may employ specific fabrics that are available. A list of manufacturers is presented in Appendix A. In most cases involving flowing water, fabrics used alone do not provide sufficient protection due to their buoyancy and their tendency to be moved by currents. Fabric used in conjunction with vegetation is often an effective solution. Fabrics are also used frequently as a bedding for revetments to prevent leaching of fine bank materials. Geotextiles used with vegetation produce the same environmental benefits as vegetation used alone. The major benefit is aesthetic, but when woody vegetation is used, riparian benefits can be significant, and there may be some aquatic benefits from shade and organic debris falling into the stream. The benefit of using fabrics with riprap is entirely structural. Fabrics have been used on streams in many locations. In areas without sufficient rainfall to support dense plant cover, supplemental irrigation is usually required if vegetation is used. Geotextiles work well in providing temporary protection until vegetation can become established at sites where they are not exposed to swift currents for prolonged periods of time. Natural geotextiles tend to function better than synthetics due to their ability to breakdown, to absorb moisture, and to create favorable growing environments.

Soil Cement - Primarily used on the upper bank, soil cement forms a protective layer over the bank. Mixed with 15% portland concrete, bank soil is compacted to provide a stable surface. To prevent structural damage, hydrostatic pressure should be reduced by adequate drainage. In areas devoid of quarried stone, soil cement is often economically effective due the availability and low cost of materials, and ease to apply. Soil cement is recommended if vegetation is difficult to establish. It should be noted that this method should not be used where traffic is expected due to the fact that soil cement is not flexible. Effectiveness of soil cement on existing projects has not been adequately evaluated.

Bulkheads - Bulkheads, or other vertical wall structures, are used on vertical or near vertical bank slopes to prevent a bank from sliding into the river. A variety of materials, such as gabions, stone, sheet metal, and timber to name a few, can be used to construct bulkheads. For timber bulkheads, it is wise to place riprap at the toe of the structure for scour protection and to tie the ends of the bulkhead into the bank to prevent severe erosion and flanking where the flow re-attaches to a natural, sloping bank. This usually requires some form of transitional protection using a sloping revetment. Bulkheads must be designed to prevent hydrostatic pressure from damaging the structure. Also, care must be taken to prevent soil loss between the piles and a geotextile filter may be necessary to prevent this.

Bulkheads can be harmful to the environment by elimination of riparian habitat, or abrupt land water transitions. Vertical walls provide little or no valuable habitat. Their poor aesthetics also count heavily against them to the extent that local planning permission may well be denied in areas. Exposed piling is ideal when the bank is used intensively for boat operations, mooring and manuvering, such as around locks and marinas. It will withstand high current velocities and wave attack, and if properly designed will be stable against severe toe scour. Submerged piling may produce adequate toe protection, but can be a serious hazard to boats. Since the bankline is vertical, piling is useful in confined sites with restricted space for a sloping bank. Conversely, a vertical piled wall on one bank may promote erosion opposite due to wave and current reflection.

Flow Deflection Techniques

Flow deflection techniques are based upon the principle that by redirecting higher velocity flows away from the bank, erosion can be reduced or eliminated in areas between structures. This procedure usually results in a lower cost than continuous armoring of the bank. Deflective structures are constructed approximately perpendicular to the flow, and therefore reduce the effective width of the river. Locally, a scour pocket develops off the end of the structure and continues downstream in a teardrop pattern. There is usually an increase in the velocity adjacent to the structure. Average cross-channel velocity may increase, decrease, or be unaffected. Generally, there is an increase in stage and/or depth for a given flow in the channel adjacent to the structure, particularly if the structure length exceeds 1/6 of the channel width. Material type, length, height, location, and orientation of the structure will affect the degree of impact. These structures are usually constructed with less disruption to the riparian community than other erosion control techniques. Effects on wildlife species are usually insignificant. Sediment accretion behind the structures may provide additional access to the river for some species, and provides good substrate for benthic organisms. Recreational benefits increase if access is provided to the structures.

The primary environmental benefit of deflective structures is the creation of additional habitat for fish species. The cross sectional changes provide diversity and, by using proper materials, suitable cover and substrate increase.

Hardpoints and Jetties - The terms hardpoint and jetty are generally regarded as being synonymous. However, for this manual, the terms are used to differentiate between differing degrees of the same basic structures. Both structures consist of a stone or soil spur that extends riverward of and perpendicular to the bank, and a stone root to prevent flanking of the structure (Figure 5.6). Hardpoints are low stubby structures that are frequently overtopped and extend riverward less than 15 or 20 feet. Jetties are generally constructed to the height of the high bank, and extend riverward more than 20 feet. Hardpoints deflect the current away from the eroding bank for only a short distance, with no attempt to change the general alignment of the river. By contrast, jetties deflect current for a considerable distance, and are often intended to alter the main flow of the river. Hardpoints and jetties are best suited to long straight reaches of river, or on the convex bankline of meanders. Structures placed on the concave bank can fail from excessive scour between structures. The main advantage of hardpoints and jetties is the low quantity of material needed to protect a given bank relative to other structural alternatives. The environmental benefits of this structure type are primarily related to fisheries and recreation. Hardpoints and jetties create a habitat diversity not found with most other structure types. Scour off the end of the structure creates deep pools and high velocity flows. Scallop areas of shallow, relatively slow-moving water provide additional habitat diversity downstream of the structures.

Cribs - Used on smaller streams on a limited basis, cribs, or log cribs, deflect erosive currents away from the bank and induce sediment deposits behind the structure. Cribs are constructed during low flow in the shape of a 30-60-90 triangle. The long side of the triangle should be towards the bank while the short end should be facing downstream so the flow will be deflected towards the center of the channel. Log used in the construction should be a minimum of 6 inches in diameter and the stone should be angular in shape and keyed into the bank 12-24 inches. The crib height should be small enough to allow flood waters to pass over the top. Crib deflectors deepen channels, create meanders, remove silt, and enhance aquatic habitat, but may cause bank erosion on the opposite side of the crib if not properly constructed. Cribs are economical if materials are located nearby and unskilled labor is used. Cribs exposed above the water may be estheticaly displeasing and the logs will need replacement due to rotting.

Dikes - Dikes are useful for bank protection where the water depth adjacent to the bank is greater than four feet, and the stream velocity is too high for other techniques. There are two types of dikes, permeable and impermeable. Permeable dikes allow water and sediment to flow through with reduced velocity while impermeable dikes are used to reduce river width. While both types of dikes are constructed perpendicular to the stream bank, permeable dikes uses timber piles as the main ingredient for construction while impermeable dikes use stone. Permeable dikes design criteria depends on sediment load and most have horizontal bracing throughout the structure. Factors that affect the design of the impermeable dikes are severity of expected flows, method of construction, and maintenance requirements. Regardless of the type of dike used the design length of the structure should be at least one-third the length of the desired protection. Since eroding bankline can be great in length, multiple dikes will be needed to produce the desired effect. Dikes can also be useful in a variety of rivers ranging from high or low gradient tributaries and secondary alluvial streams. Permeable dikes require flows with high sediment loads to be fully effective whereas impermeable dikes do not require a high concentration of sediment to protect the bankline. Dikes become more economical than riprap as the depth of the water increases but, it is safer to a continuous form of bank protection such as revetments on bank curves greater than thirty degrees. Dikes produce deep and narrow stream channels but become ineffective when overtopped with high water.

Fence Dikes - Fence dikes are very similar in design to hardpoints and jetties. The difference lies in the materials used. Fence dikes consist of wood planks or wire mesh attached to timber piles extending riverward of the eroding bank. Stone is often used as a foundation, or is placed at the end of the structure to reduce scour. When wire mesh is used, it is typically backfilled with another material such as brush or hay. The impact to the channel from this type of structure is somewhat different than for stone-fill jetties or hardpoints. Since fence dikes are relatively permeable, less scour occurs riverward of the structure's end. Sediment accretion behind the structure is often more extensive than for less permeable structures. Environmental benefits and considerations for this structure type are the same as for hardpoints and jetties. Recreational benefits are less for fence dikes than for hardpoints or jetties because they do not improve access to the river. Fence dikes have been used extensively on rivers throughout the US with mixed success. They are more prone to damage than hardened structures, particularly from ice or debris. Fence dikes require more maintenance than hardpoints or jetties.

Fences - Used in small low gradient streams, fences are constructed parallel to the bank line to promote sedimentation. Fences are made of a variety of materials but the prime materials used are wood and wire. On sandy bottoms, fence posts should be spaced 6 to 10 feet apart and driven 15 feet into the ground if stream velocities over 15 feet per second are expected. To provide extra protection, brush, hay bales, used tires, or rock can be placed between the fence and the stream bank. Fences can be designed to deflect stream low or to trap debris. Eliminating the problem of constructing a stable foundation, fences are more economical than riprap or matting methods. Since fences are constructed away from the bank, they promote sedimentation but are vulnerable for damage due to ice flows or large debris from heavy floods.

Energy Reduction Methods

Energy reduction methods function by reducing the ability of the river to erode bed and bank material. In the case of vanes and fence revetments, this is accomplished by reducing boundary shear and secondary helical currents. Selective clearing and snagging and chute closures both function by reducing the most severe flows along eroding banks. Vanes and fences have little effect upon the morphology of the river. Sediment transport may be slightly reduced in the immediate vicinity of the structures, but this is of little consequence. They are intended to have minimal impact upon the channel geometry. On the other hand, clearing and snagging and chute closures can both have a dramatic effect upon the morphology of the river. Clearing and snagging reduces stages, changes the velocity distribution at a section, and can increase sediment transport through the reach. Selective clearing of bars and islands can cause realignment of the main channel of the river. Chute closures or channel blocks increase the flow in the main channel and reduce or deplete flows in the chute. The stage of the river will increase upstream of the structure, particularly during high flows. Both velocity and sediment movement may increase slightly in the channel. If flow is eliminated in the chute, sediment deposition will eventually fill it. Vegetation encroachment will occur in the chute, further reducing the flood capacity of the section. Most of these methods cause sediment accretion, which improves substrate for boring macroinvertibrates. The sediment may cover other more-desirable habitat such as cobbles. The associated hydraulic changes may adversely affect other aquatic species due to a loss of higher velocity habitat and the potential for elevated water temperature. These methods generally have very little impact upon riparian habitat. They may positively or adversely affect recreation and aesthetics.

Vanes - Vanes are structures placed within the channel at a slight angle to the normal flow that reduce the secondary currents and thus reduce the erosive capacity of the river. The two most common types of vanes are Iowa Vanes, baffle vanes, and stone vanes. Iowa vanes are small flow-training structures (foils), designed to modify the near-bed flow pattern and redistribute flow and sediment transport within the channel cross-section. The structures are typically installed at an angle of 15.20^{B} to the flow, with a height of 0.2 - 0.4 times local water depth at designed stage. The vanes function by generating secondary circulation in the flow. The circulation alters magnitude and direction of the bed shear stresses and cause a change in the distributions of velocity, depth, and sediment transport in the area affected by the vanes. As a result, the river bed topography may be altered by selective layout of the structures. Baffle-type vanes are structures consisting of boards attached to piles that are placed in series in the stream to disrupt the secondary currents that cause erosion on the outside of meander bends. The number, locations, spacing, orientation, size, and height of the vanes are critical to success and must be determined from careful analysis. Stone vanes are low stone structures angled approximately 15^{o} normal to the flow. They are overtopped by all but the lowest flows.

Because vanes stop erosion by modifying secondary circulation, no bank sloping or treatment is necessary. Aquatic benefits are not destroyed, and once vegetation becomes re-established on the eroding bank, riparian habitat and aesthetic benefits are improved. During low water, the vanes are not very appealing visually, and there may be some hazard to navigation and to recreationists using the stream.   Vanes have not been used extensively. Prototype vane systems have been installed in a couple of midwestern streams, including the East Nishnabotna River in Iowa. It is too soon to evaluate the success of the prototype demonstration at this site, but sedimentation was induced between the structures and the bank in model studies. The sediment deposition may reduce the effectiveness of the structures, and could induce additional erosion along the bank due to the reduction in channel capacity. Vanes have been used successfully to ameliorate shoaling problems at water intakes and bridge crossings.

Clearing and Snagging – For flood control on small streams, conventional clearing and snagging has been used to remove all obstructions from the channel and to clear all significant vegetation within a specific width on both sides of the channel. Key aspects of selective clearing and snagging involve selective removal of vegetation based on size, condition, species, or location; removal of only those snags that are major flow obstructions; use of hand labor and small equipment when feasible, and rigid access controls when heavy equipment must be used; protection of existing vegetation of disturbed areas; and greater reliance on multidisciplinary teams in all phases of project planning and management. Disturbed areas should be restored to natural contours, and preserved trees should be spaced at irregular intervals. Natural sloughs, drains, and flood-plain depressions should be left in their original condition. Because of the limited improvement in flow hydraulics (upper flow capacity limit roughly equivalent to bankfull discharge), selective clearing and snagging is most often used to provide relief from high frequency nuisance flooding, for drainage improvement in agricultural areas, and recreational benefits. Increased hydraulic conveyance results from changes in the resistance to flow values in uniform flow equations. Vegetation, channel irregularity, obstruction to flow, and design flow conditions should be considered in estimating improvements in resistance coefficients.

Channel Blocks - Used in small to medium streams or on side chutes of larger streams, channel blocks are used to prevent stream flow from forming a new channel by keeping the flow in the desired channel. Constructing during low to normal stream flows, a rectangular framework of logs, with a minimum diameter of 6 inches, and stone, that can be conveniently handled, are placed in the mouth of the channel. The structure should contain riprap on the downstream side to prevent scour and be lower than the existing bankline to permit flood water to pass through the secondary channel. Channel blocks effectively divert streamflow but, are ineffective on large streams with large side channels. If the material is economically available, unskilled workers can be used in the construction of channel blocks to cut costs. However, logs must be replaced as they decay. Aquatic habitat is enriched as a result of deep channel flows

Fence Revetments – Fence revetments are used to solve a variety of bank protection problems. They are constructed parallel to the bank and to the flow at, or riverward of, the toe of the bank slope. Fences are constructed of wood or wire and are pervious. Stream velocity behind the structure is significantly reduced, thereby reducing erosion. Because fences stop erosion by reducing secondary currents and circulation, no bank sloping or treatment is necessary. Aquatic features are not destroyed, and once vegetation becomes re-established on the eroding bank, riparian habitat and aesthetic benefits are improved. Fences have been used successfully on many rivers. They are prone to damage from ice and debris, and must be regularly maintained.

Grade Control Structures - These are structures designed to reduce channel grade in natural or constructed watercourses to prevent erosion of a channel that results from excessive grade in the channel bed or artificially increased channel flows. This practice is used to stop headcut erosion or stabilize gully erosion. Grade stabilization structures may be vertical drop structures, concrete or riprap chutes, gabions, or pipe drop structures. Permanent ponds or lakes may be part of a grade stabilization system. Concrete chutes are often used as outlets for large water impoundments where flows exceed 100 cfs and the drop is greater than 10 ft. Where flows exceed 100 cfs but the drop is less than 10 ft., a vertical drop weir constructed of reinforced concrete or sheet piling with concrete aprons is generally recommended. Small flows allow the use of prefabricated metal drop spillways or pipe overfall structures. Designs can be complex and usually require detailed site investigations. Design of large structures (100 cfs) requires a qualified engineer. The National Engineering Handbook (Drop Spillways, Section 11, and Chute Spillways, Section 14) prepared by the USDA Natural Resources Conservation Service gives detailed information useful in the design of grade stabilization structures.

Low-head weirs are essentially the same type of construction as the check dam, built from rocks, logs, or other material, but intended for use in lower order perennial streams for water quality improvement and habitat enhancement. Weirs are most successful in streams with discharge not exceeding 6m33/s. Benefits include formation of pool habitat, collection and holding of spawning gravels, promotion of gravel bar/riffle formation, trapping suspended sediments, reoxygenating water, allowing organic debris deposition, and promotion of invertebrate production.

Slope Stabilization Methods

If failure is due mainly to geotechnical factors like drawdown or seepage, protection against hydraulic erosion may not be the best treatment. On the other hand, geotechnical failure may represent a delayed response to continuing scour at the bank toe, in which case toe protection against hydraulic erosion is essential. When geotechnical factors alone are involved, this usually results in mass failure of the embankment material. Several different types of mass failure can occur in banks. These include sliding along a deep failure surface, shallow slips, and lock failures. Many factors affect mass failures. They include soil type, bank slope geometry, surface and ground water flow regime, infiltration, surcharge loading, tension cracking, and vegetation. Each factor's contribution to the failure must be identified before an appropriate solution can be selected. Slope stabilization techniques typically involve large-scale modification to the bank. This can seriously disrupt the riparian environment, and may affect aesthetics and recreation. Impacts to the aquatic community are generally slight, but reductions in sediment supply and the value of existing bank cover should be addressed.

Grading – The best structural solution to most geotechnical failures is to regrade the bank to a lower angle and to protect the toe and lower bank from further erosion that might otherwise over-steepen the slope. If weakening of the bank is also a factor, steps must be taken to prevent damage by limiting access or modifying the activities responsible. Shallow slips and dry grannular flows are generally addressed with minor bank modifications. Deep seated rotational slips are a severe form of bank instability and, because the failure surface is located deep inside the bank, surficial or shallow treatments are inadequate to deal with this type of failure. Major regrading of the bank coupled with toe protection and improved drainage may be needed to achieve stability. If space limitations preclude complete regrading, a structural retaining wall must be incorporated into the design. In the field a geotechnical site survey must be performed to identify and quantify all the relevant factors and bank parameters before any firm conclusions can be drawn regarding the cause of failure and detailed design for stabilization.

Geogrids and Geotextiles - As a surface failure, dry granular flow is easily dealt with using soil reinforcement by geogrid, geotextile or suitable living vegetation coupled with lower bank armouring to prevent undercutting. If weakening is a factor due to trampling or mechanical damage to the upper bank, then either active bank management should be employed to reduce or eliminate the activity responsible, or surface protection must be extended up the bank to prevent significant impacts on bank stability.

Retaining Walls – If regrading a shallow or rotational failure is precluded by lack of space, the over-steep bank can be stabilized using a vertical retaining wall, but this solution has severe environmental impacts and low aesthetic value.

Drains – Improvement of subsurface drainage is the key to preventing wet earth flow failures. Steps involved include the reduction of seepage pressures by encouraging free drainage, with a suitable filter installed to prevent piping erosion. Drainage may be achieved using perforated pipes or French drains. Filters may be granular, geotextile or vegetative. This is a serious form of instability that will require a geotechnical site survey to establish the details of the problem and a careful analysis of bank seepage to support the selection of an appropriate solution.

Techniques that Address Bank Weakening

The most direct engineering solution to leaching is to strengthen the soil artificially by injecting grout or resin into the bank. This action is expensive and would usually only be cost-effective where the bank is highly vulnerable to leaching, and allowed adjustment of the bankline is precluded by space limitations. It is difficult to detect leaching in the field without a detailed examination of the soil profile and laboratory analyses of soil mineralogy and pore water chemistry.

In the cases of serious trampling of the bank, a management solution through limiting access is preferable, but where this is not possible engineering solutions must strengthen the soil surface to increase its bearing capacity. Conventional treatments include paving using concrete or bitumen to create footpaths and animal ramps, but such solutions are visually intrusive and may be inappropriate in many locations. Modern alternatives include geogrids and cellular concrete blocks that provide surface protection while allowing vegetation to grow through them, producing a natural appearance to the stabilized bank.

The most cost-effective structural intervention to prevent destruction of riparian vegetation is a fence. The creation of a riparian buffer zone by fencing out farm stock and people has been shown to be the single most beneficial action that can be taken when attempting to stabilize protect and conserve a river bank. Ideally, the corridor created should be sufficiently wide to allow a stand of vegetation between the fence and the low flow water edge, but even corridors of just a few meters have been found to produce real benefits. Where access to the bank cannot be denied, destruction of vegetation can be prevented structurally using buttresses to stabilize the roots of undercut trees, geogrids and cellular blocks to provide surface protection for riparian vegetation, and pocket fabrics to support aquatic and emergent vegetation.

Mechanical damage is best dealt with through active bank management to reduce or eliminate the impacts of human activities in damaging the bank; where this is not possible a structural solution must reinforce the bank, reducing its vulnerability to mechanical damage. The precise form and strength of protection depends on the type and intensity of activity. For example, a length of bank routinely used for mooring may need heavy structural protection using sheet piling, while a reach that is intensively used for competition fishing may need wooden piles and access steps to prevent damage and erosion around fishing pegs. Where activity is less intense, lighter, hybrid structures may suffice. For example, the use of a geogrid may provide the increased bearing capacity to prevent damage by motor vehicles parking near the bank top at camping sites and picnic areas during summer months.

Excess positive pore water pressures are potentially disastrous to bank stability and are also often responsible for the failure of bank schemes. Structural solutions must dissipate pressures by allowing drainage while retaining soil particles and preserving the soil fabric. The detailed design of subsurface drainage works is a specialized area of geotechnical engineering, but generally schemes use a variety of perforated pipes and filters to eliminate excess pressures.

Desiccation can lead to cracking and crumbling of soil that significantly reduces its operational strength, promoting erosion and instability. A light reinforcement system should be sufficient to protect the bank from desiccation and this may utilize various geogrids, geotextiles, and suitable types of vegetation.

Soil Bioengineering Techniques

Toe Zone

This is the zone that will need to be protected from undercutting with treatments such as stone or rock revetments, gabions, lunkers, log revetments, deflector dikes, cribs, rock and geotextile rolls, root wads, or a combination of materials. The zone rarely has vegetation employed in it alone, but when vegetation is employed, it is used in combination with materials that extend below the normal flow of water and above it. The principle is to keep high velocity currents from undercutting the bank either through armoring the bank or deflecting the currents away from the site of concern. Vegetation can then be used either above the armor or in between and above the deflecting structure.

Stone or rock revetments in a bioengineering application are used at the toe in the zone below normal water levels and up to where normal water levels occur. Sometimes, the stone is extended above where normal flow levels occur depending on the frequency and duration of flooding above this level. Then, vegetation is placed above it in a bioengineering application. Stream gage information helps in making this judgement. Unfortunately, there are no set guidelines for how far up the bank to carry the revetment except to say that it should be applied below the scour zone up to at least the level where water runs the majority of the year. Engineering Manual 1110-2-1601, Change 1 (Corps of Engineers, 1994) gives guidelines for riprap toe protection.

One such rock revetment for toe protection was used in conjunction with vegetation above it on Crutcho Creek, Tinker Air Force Base, Oklahoma . In this example, the creek is flashy and often reaches or exceeds the top of bank during the spring of each year for a few days. The rock toe extended from the bed to about 1/3 the height of the bank (Figure 5.7). This treatment has been successful in this type of setting after several floods exceeding the top of the bank.

Rock toes are also used streamward or just below other materials such as hay bales or geotextile rolls. In one example, Omaha District recently used rock riprap below a large hay bale cylinder covered with a fabric (rope mesh) made from woven fibers of coconut husks called coir. The riprap weighed about 1.5 tons/ft and was about 3.5-ft deep. Then, vegetation in the form of dormant willow poles (discussed below) was placed above this (Figures 5.8 and 5.9).

In another example, a rock roll (Figure 5.10) was used on the Rhine River in Dusseldorf, Germany, below an installation of wetland vegetation grown in geotextile mats made from coir. The large rock was wrapped in a polyethylene type of rope mesh and installed in the following fashion:

1) A ditch is dug;

2) The rope mesh is placed in the ditch so that enough of it is overhanging the ditch on the riverward side to wrap around the rock and have some left on the shoreward side on which to place more rock;

3) The rock is placed on the rope mesh;

4) The rope mesh is wrapped around the rock with a portion of it running up the shoreward side; and finally

5) More rock is backfilled on top of the rope mesh to hold it all firmly in place. This rock roll serves to protect the treatment from undercutting. The rope mesh contains smaller rocks and strengthens the system and is similar to the function of gabions which are discussed below.

It should be mentioned that this whole system of rock rolls and geotextile mats with wetland grasses or grass-like plants, such as sedges, were placed in between large rock transverse dikes (Figure 5.11). The dikes were already there before this treatment was installed and divert river currents away from the banks. The rock roll (toe protection), the transverse dikes, and the geotextile coir mats, work together to obtain wetland plant establishment and erosion control. Prior to the installation of plants, even though the transverse dikes were present, an asphalt revetment used to control erosion failed because water got behind the asphalt and pushed it out. This system has been in place from 1991 to present and has withstood a large flood in 1994, the largest in the last decade, with more than a 7 m fluctuation above normal flow. The flood overtopped the treatment for several months. Because of the wetland plants' flood tolerance, the rock toe, and transverse dikes, they survived and are still controlling erosion. A key wetland plant species instrumental in the treatment's success was a sedge, *Carex hirta*[1].

Gabions are wire mesh baskets filled with rock and formed as boxes of various dimensions. The wire is either galvanized or covered with a plastic coating to increase durability. Gabions are tied together to become large, flexible, structural units and can be stacked in tiers. They can be installed in the toe zone to prevent undercutting and can be stacked or run as a revetment of gabion mattresses up into the splash and bank zones (Figure 5.12). They can be used in conjunction with vegetation in several ways. Often live willow whips are placed in between the tiers of boxes back into soil that facilitates sprouting. When they are used as a gabion revetment and rock toe, vegetation can be placed in the splash and bank zones above them. Gabions should be used with caution in streams that have high bed load movement with cobbles and gravels that may break the wire mesh. Also, they are susceptible to vandalism and to undercutting/overturning. If used in a stacked fashion, a geotechnical engineer should be consulted to determine stability; otherwise, overturning and sliding may be a problem.

Figure 5.13 is two schematics (two different versions) of a hard stabilizing structure for a toe. This structure is called a LUNKERS, which is an acronym for "Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids." The LUNKERS is designed to provide overhanging shade and protection for fish while serving to stabilize the toe of a streambank. They were first used by the Wisconsin Department of Natural Resources and described in detail by Vetrano (1988). They have since been adapted for use by the Illinois State Water Survey. They are made from treated lumber, untreated oak, or materials made from a combination of plastic and wood and are constructed by nailing planks to the top and bottom of 15- to 20-cm spacer logs. These planks form stringers, which tie into the streambank at right angles. Planks are nailed to the top and bottom stringer boards and run parallel to the streambank. The entire structure forms a crib, which can be constructed onshore and moved by a loader or backhoe to the installation site.

Once in the stream, the LUNKERS is placed in position and anchored by driving 1.5-m lengths of steel-reinforcing rod through predrilled holes in the structures and then into the streambed. These structures are set in a line that simulates the outside bend of a meander. After the structures are in place, the area behind them is filled with rock riprap, which also is used to cover the structure, and then the entire area is covered with soil (Hunter, 1991). Often, the soil is planted with various kinds of vegetation, either woody or herbaceous. Care must be taken to tie the ends into the bank with a transition of rock or into a hardpoint to prevent flanking.

Another hard structure placed in the toe zone to stabilize the toe is a "Bank Crib with Cover Log" (Figure 5.14). This is described by the USDA Forest Service (1985). Like the LUNKERS, it is used to protect unstable streambanks at the toe while at the same time providing excellent overhead cover for fish. The design is a simple crib with abutment logs extending as far back into the bank as necessary to assure structural stability (1.3 to 1.8 m in stable soils and 3 m or more in unstable soils). The lower abutment logs should be near water level and should extend 45 to 60 cm from the bank. The cover log can then be pinned to the crib log and the lower abutment. The structure can be from one to several logs high, depending upon bank height. The only materials required are logs on site and 1.6 cm rebar to join the logs. Installing structures is fairly time consuming, due to the amount of digging required. One crew should be able to install 6 to 9 m of crib (two crib logs high) per day if logs are reasonably close to the site. Water adjacent to some eroding banks requiring abutment work is sometimes too shallow to make effective use of cover logs. It has been noted by some that rocks need to be added below the crib log and upstream and downstream from the structure to avoid scour and flanking respectively.

Log revetments are similar to bank cribs with cover logs except these are used to harden the toe and continue up the bank by lining the bank with logs (Figure 5.15). Then, flood-tolerant plants are placed at the top of and shoreward to the revetment. Depending on the height of the revetment, this may be in the splash, bank, or terrace zones. They are placed with butt ends facing upstream and are overlapped in a shingle fashion. They are secured with cables that are looped around the logs and then are fastened to dead men in the bank. Care must be taken to ensure their longevity by placing rock on both the upstream and downstream ends to prevent flanking of the structure. Rock should also be placed at the toe of the structure to prevent scour.

Figure 5.16 shows a schematic of a log revetment used on the Roaring Fork River, Colorado, near Basalt. A geotextile coir roll, called a Vegetations-Faschinen in Germany, where it originated, is placed above the top log in the revetment so its top is just even with or slightly above the normal water level. The roll is often referred to in this country under various trade names such as Fiber Roll, Fiberschine, and Bio-log. It is used in conjunction with a geotextile mat which is placed shoreward of the roll, backfilled with soil, and planted or seeded with wetland plants. The geotextile roll and mat trap sediment, allow plants to be planted in them, and are biodegradable. Note that the top log is placed in an overhanging fashion with the coir roll on top to provide shade and cover for fish. Figure 5.17 shows an installed log revetment on the Roaring Fork River. On one reach of the Roaring Fork, this structure failed because it was not keyed into the bed of the stream. Scour at the toe caused structure failure. On another reach, it worked just fine. These structures must be properly protected at the toe and at the upper and lower ends with rock and hard points, respectively.

Root wads are live or dead logs with root masses attached (Figure 5.18, See Bowers, Land & Water 1992). These are also used in the toe zone to protect it from undercutting, but must be used in combination with other materials. The fans of the root wads provide an interlocking wall protecting the streambank from erosion. The voids within and between the root wads are filled with a soil mix and planted with live, willow clumps or root pads. The root wads are laid on top of a keyed-in shelf of stone and support logs. This shelf includes a layer of bottom support logs flush with one another, shingled together, and running parallel to the streambank. The root mass should be a minimum of 5-ft in diameter and angled slightly upstream towards stream flow. This treatment should be placed at a base elevation that is consistent with water levels during the major part of the growing season, i.e., June through September. The bottom two-thirds of the root wad should be in water during that period of time. The upstream and downstream ends of the root wad treatment should be tied into hard points made from rock or some natural hard feature so as to prevent flanking.

Figure 5.19 shows a treatment using root wads on the Upper Truckee River in California near South Lake Tahoe, where this treatment and others were monitored for a couple of growing seasons. Various local flow velocities were measured along the treatment on the fall of the hydrograph. These ranged from 1.6 to 4.0 fps at .6 depth of flow and 4 ft out from the right bank. The root wads sufficiently reduced local flow velocities so that vegetation had a chance to get established and stabilize the bank despite a major flood in the spring and summer of 1995 where floodwaters overtopped the bank. Rosgen 1 noted that on a root wad treatment on the Blanco River in Colorado, that local velocities in the vicinity of the root wads were 12 fps and yet willow clumps installed in with the root wads and the root wads themselves did not fail.

Deflector dikes are any constructed protrusion into the water that deflect the current away from the eroded bank. These consist of: transverse dikes, hardpoints, groins, bendway weirs, and stream barbs. They are usually made of rock, but other materials such as logs or trees can be used. As mentioned above in the Dusseldorf, Germany, example, bioengineered treatments often use vegetation between deflector dikes. The dikes and the bioengineered treatments work as a system to stabilize the streambank. Transverse dikes differ from hardpoints or groins by projecting further out into the stream. Bendway weirs and stream barbs are low rock sills. Flows passing over them is redirected so that the flow leaving the structure is perpendicular to the centerline of the structure. Derrick (1996) describes the construction and use of bendway weirs both on the Mississippi River and on smaller streams in northern Mississippi. In the latter case, bendway weirs were successfully used, in part, with a dormant willow post method of stabilizing the streambank (to be discussed below). Shields et al. (1995) describe the benefits to aquatic habitats on small streams in northern Mississippi by use of such weirs. The structures increased pool habitat availability, overall physical heterogeneity, riparian vegetation, shade and woody debris density. To design deflector dikes with vegetation, persons are needed with training both in hydraulic engineering and bioengineering working as a team. Hydraulic engineers should be consulted for design, construction, and placement of the deflector dike and bioengineers or someone with training in botany should be consulted for use and placement of the vegetation.

A combination of materials, as mentioned above, can be used in the toe zone. Deflector dikes can be used with plants incorporated in the dike system for erosion control as well as fisheries habitat. Figure 5.20 shows a schematic of a coir geotextile roll.   As illustrated in the figure, it is used in combination with rock at the base and around the ends with some openings for the ingress and egress of fish and other aquatic organisms. The coir is stuffed into a rope mesh material made either out of coir itself or of polyethylene. The roll is planted with emergent aquatic plants. The coir accumulates sediment and biodegrades as plant roots develop and become a stabilizing system. Figure 5.21 shows several on a German stream. Each structure serves to redirect the current away from the bank so that vegetation can be installed in between. The plants in the structure furnish shade and cover for aquatic life. While the rock of the structure would be in the toe zone, the roll and the aquatic plants would be on top of the rock and abreast of it. The roll would actually grade into the next higher zone, the "Splash Zone."

Splash Zone

The coir roll mentioned above can also run parallel to the bank with rock in the toe zone providing the foundation and additional protection at the base of the roll itself. Sometimes, the coir roll is all that is used in the toe zone when currents or waves are not strong or big enough to justify rock. Then, vegetation is planted or grown in the roll to form part of the splash zone. Figure 5.22 is a schematic of a coir roll abutted to an unshaped bank with some backfill. Figures 5.23 a-c show such a treatment in a stream in Germany and planted with emergent aquatic vegetation, such as bulrushes, iris, and sedges. Vegetation can be grown in the roll at a nursery and then transferred to the planting site with vegetation almost established.

Coir rolls and emergent aquatic vegetation have also been used in this country recently. One such use was on the North River near Colrain, Massachusetts. It was monitored as a part of this work unit for two growing seasons. That case study is presented in Volume II.   Both single and double coir rolls were used in different sections of the streambank. In the latter case, another roll was placed upslope from the first one. Both were planted by inserting clumps of emergent aquatic plants in them. Where overhanging banks occurred and were void of woody vegetation, an evenly sloped bank was achieved by shaping and backfilling using a small front-end loader. Shaping, however, was minimized where possible in an effort to prevent disturbance of the bank and existing vegetation. It should reiterated that the coir rolls should be keyed well into the upper and lower ends of the reach being treated. The authors discovered after the two-year formal monitoring period, that the coir rolls had apparently been flanked at the upper end as a result of flooding in the spring of 1995 and that sections of the project unravelled.

The clumps of emergent aquatic plants mentioned above that were placed in the coir rolls were grown from seedlings placed in a coir wrapping and allowed to develop hydroponically (in water without soil, but with nutrients added). This leads to a well-developed, but light and easily transportable plant unit with roots readily established and poised to grow in a planting medium, such as the coir roll or in a soil substrate.

Coir fiber mats made in various thicknesses are also used in the splash zone. These are often prevegetated at the nursery with emergent aquatic plants (Figure 5.24 a-b) or sometimes sprigged (use of single or multiple rooted stems inserted into substrate) with emergent aquatic plants harvested from local sources. When prevegetated at the nursery, the fiber mats have the advantage of being light and can be lifted in rolls or smaller mats and transferred directly to the planting site where immediate establishment is required. They are usually tied into or keyed into whatever is used as the toe material. In the example on the North River above, 1-inch thick mats were prevegetated and tied into the coir rolls. Coir fiber mats have the attributes of high tensile strengths, the ability to trap sediment, they are pH neutral, they facilitate root development because of the fiber network, and they are slow to biodegrade. These types of vegetated coir mats have also been used on dredged material in coastal environments with wave environments. Knutson et al. (1990) reported successful trials of sprigging emergent aquatic plants into such mats. This success was attributed, in part, to the attributes mentioned above, such as sediment entrapment. The blankets trapped sediment very well on the North River which aided plant establishment.

Single-stemmed sprigs and clumps of emergent aquatic plants and flood-tolerant grasses or grass-like plants, e.g., rushes, sedges, can be planted shoreward of hard rock toes, coir rolls, and fiber mats. They can even be used in lieu of the fiber mats if the site-specific conditions are appropriate. This may mean that the soils are more cohesive, i.e., have more clay in them, the stream discharges at that level are not as high.

Our focus in the splash zone, so far, has been on use of emergent aquatic and other herbaceous plants. Woody plants are also used in the splash zone. For these, wetland plants are used that can also withstand periods of dryness. The woody plants should be those that can sprout roots and branches from the stem. These include willow, some species of alder dogwood, and several other species. Several possible species are listed by the Georgia Soil and Water Conservation Commission (1994) and Gray and Sotir (1997). Sometimes, woody plants may be all that are suited to the splash zone. At times, the bank geometry is very steep down to the normal flow level without a shallow water zone for emergent aquatics or, the stream system has extreme fluctuations and large sediment loads that would drop on emergent aquatics and bury them.

Bioengineering techniques that utilize woody plants include: brushmattress, brush layering, vegetative geogrids, dormant post method, dormant cuttings, and dormant root pads. All of these are usually used in combination with hard structures or materials that either deflect the current away from the bank or protect the toe and upper and lower ends. For instance, dormant root pads are used with root wads that were discussed above for the toe zone.

Brushmattress. A brushmattress, sometimes called brush matting or a brush barrier, is a combination of a thick layer (mattress) of interlaced live willow switches or branches and wattling. Both are held in place by wire and stakes. The branches in the mattress are usually about 2 to 3 years old, sometimes older, and 1.5 to 3 m long. Basal ends are usually not more than about 3.5 cm in diameter. They are placed perpendicular to the bank with their basal ends inserted into a trench at the bottom of the slope in the splash zone, just above any toe protection, such as a rock toe. The branches are cut from live willow plants and kept moist until planting. The willow branches will sprout after planting, but care should be taken to obtain and plant them in the dormant period, either in the late fall after bud set or in the early spring before bud break. A compacted layer of branches 10 to 15 cm thick is used and is held in place by either woven wire or tie-wire. Wedge-shaped construction stakes (2 X 4 X 24 " to 2 X 4 X 36", diagonal cut) are used to hold the wire in place. A guage and type suitable for tie-wire is No. 9 or 10 galvanized annealed. It is run perpendicular to the branches and also diagonally from stake to stake and usually tied by use of a clove-hitch. If woven wire is used, it should be a strong welded wire (2- by 4-in mesh). The wedged-shape stakes are driven firmly through the wire as it is stretched over the mattress to hold it in place. The wedge of the stake actually compresses the wire to hold the brush down. Wattling is a cigar-shaped bundle of live, shrubby material made from species that root very quickly from the stem, such as willow and some species of dogwood and alder. These bundles are laid over the basal ends of the brushmattress material that was placed in the ditch and staked. The procedure of making wattling bundles and installing them over the brushmattress material is presented in more detail below (These procedures are modified after Leiser (1994).

Wattling bundles may vary in length, depending on materials available. Bundles taper at the ends and this is achieved by alternately (randomly) placing each stem so that about one-half of the basal ends are at each end of the bundle. When compressed firmly and tied, each bundle is about 15 to 20-cm in diameter in the middle. Bundles should be tied with either hemp binder twine or can be fastened and compressed by wrapping "pigtails" around the bundle. Pigtails are commonly used to fasten rebar together. If tied with binder twine, a minimum of two wraps should be used in combination with a non-slipping knot, such as a square knot. Tying of bundles should be done on about 38-cm centers. Wattling bundles should be staked firmly in place with vertical stakes on the downhill side of the wattling not more than 90 cm on center and with the wedge of the stake pointing upslope. Also, stakes should be installed through the bundles at about the same distance, but slightly off-set and turned around so their wedge points downslope. In this way, the wedged stakes, in tandem, compress the wattling very firmly. Where bundles overlap, an additional pair of stakes should be used at the midpoint of the overlap. The overlap should be staked with one pair of stakes through the ends of both bundles while on the inside of the end tie of each bundle. Figures 25 a-b show a schematic of a brushmattress and wattling. Figures 26 a-c show a sequence of installing a brushmattress with wattling at a workshop. It should be noted that because of the workshop setting at a mild time of the year, non-dormant vegetative material is being used. Normally, one would preferably use dormant material.

Both brushmattress and wattling should be covered immediately with soil and tamped. Soil should be worked into both the brushmattress and wattling by by both tamping and walking on it. All but the edges of the brushmattress should be covered with soil and about 75 percent of the wattling should be covered leaving some of each exposed to facilitate sprouting of stems rather than roots.

A brushmattress without any rock toe was used on the North River, Massachusetts, and performed quite well for two growing seasons until unraveling started to occur, again because of a lack of toe and upper and lower end protection. This was in a reach where a bankfull discharge was experienced with an associated average bankfull velocity estimated estimated at 6.5 fps. The 350 ft radius of curvature in the project reach, as measured off of a 1981 aerial photograph, results in increased localized velocities (Goldsmith, 1993).

Brush layering. Brush layering, also called branch layering, or branch packing, is used in the splash zone, but only in association with a hard toe, such as rock riprap, in the toe zone. It can also be used in the bank zone as discussed later. This is a treatment where live brush that quickly sprout, such as willow or dogwood species, are used in trenches. Trenches are dug 2-6 feet into the slope, on contour, sloping downward from the face of the bank 10 to 20 degrees below horizontal (Figures 27-28). Live branches are placed in the trench with their basal ends pointed inward and no more than 6 inches or more than 18 inches of the tips extending beyond the fill face (Leiser, 1994). Branches should be arranged in a criss-cross fashion. Brush layers should be at least 4 inches thick (Leiser, 1994) and should be covered with soil immediately following placement and the soil compacted firmly.

Brush layering (branch packing) was used successfully on the Little Patuxent River in Maryland (Figure 5.29). There, it was used in combination with live fascines (wattles) and live pegs (Bowers, 1992). Rock riprap was placed at the toe of the streambank for added protection. Bowers (1992) reported that the top growth of the live fascines, live branches in the branch layering, and live pegs (live stakes or cuttings) provides coverage of and protects the streambank during storm events. The species used included black willow and silky dogwood. Branch layering and live fascines were used in the low energy zones of the river, i.e., along the beginning and end of outside meanders. For the areas where the thalweg came in contact with the streambank on the outside of the meander, root wads were used for protection and stabilization (Bowers, 1992).

Vegetative geogrid. This is a system that can be used in the splash zone and actually extend further up the bank into the bank and possibly terrace zones. The system is sometimes also referred to as "fabric encapsulated soil." It consists of successive walls of several lifts of fabric reinforcement. In between the lifts are placed 5- to 10-ft long live willow whips. This system is described by Miller (1992) and was used successfully on Acid Brook in New Jersey. It was also used on the Upper Truckee River near South Lake Tahoe along with a few other treatments. The design, according to Miller, is based on a dual fabric system modeled after synthetic fabric retaining walls used by engineers for road embankments and bridge abutments. The generic system is shown in Figure 5.30. Two layers of coconut fiber-based fabric provide both structural strength and resistance to piping of fine material. The inner layer is a loose coconut fiber blanket held together by synthetic mesh netting and is used to trap finds and prevent piping. The outer layer is a strong, woven coir fabric to provide structural support. Sometimes, the latter fabric is substituted by even stronger, more durable synthetic materials, that are formed by a matrix of geosynthetic bands. The disadvantage of the latter materials, however, is that they are not very biodegradable. Of course, vegetation would mask the materials so they are not visible.

Miller (1992) describes building the lifts of fabric-reinforcement as follows:

> "To build the streambanks, we would first lay down a layer of each fabric in the appropriate location. We'd place fill material, compact it, and wrap the exposed fabric over the face of the fill. The fabric would be keyed back under the next

layer with wooden stakes. We'd progress upwards from layer to layer, whether the slopes were vertical or at a 3:1 slope."

Figures 5.31 and 5.32 show photographs of the Upper Truckee River site both before and after construction. The latter figure was taken in July 1995 after an extended high flow period from May 21 through July 21. There, Mr. Matt Kiese[1] (pers. communication) described building the lifts with the use of long angle iron forms. The angle irons were 8 ft long and were fashioned to form a frame into which plywood boards were inserted. Then, the forms were wrapped with two fabrics similar to those described above and soil dumped into the forms and compacted. The fabrics were wrapped back over the soil and the forms removed. Willow whips were laid on top of each lift and then the next lift was prepared. The installation at the Upper Truckee was no more than five feet tall and 123 ft long. Care must be taken to provide rock or some other hard material at each upstream and downstream end to prevent flanking of the treatment. For instance, one may either tie into existing vegetation, such as trees, or create hard ends by placing rock. Also, it is important to prevent scour at the bottom lift and to provide a good footing by creating a ditch and filling it with cobble or rock. The first lift is placed on top of the cobble ditch. The ditch at the Upper Truckee River site was about 2-ft wide by 2-ft deep.

Dormant Post Method. This treatment consists of placing in the splash zone and perhaps the lower part of the bank zone dormant, but living stems of woody species that sprout stems and roots from the stem, such as willow or cottonwood. Willows are normally used and are cut into 10-14 ft posts when the leaves have fallen and the tree is dormant. The dormant posts store root hormones and food reserves (carbohydrates) that promote sprouting of stems and roots during the growing season. According to Roseboom (1993), dense stands of 4-6 year old willows make the best harvesting areas. He also uses posts that are 4-6 inches in diameter at the base. His examples are based on fast-growing eastern species, however, and smaller willow may have to be used in the western states.

Roseboom (1993) prescribes shaping a bank to a 1:1 slope with the spoil placed in a 6-inch deep layer along the top of the bank. In major erosion sites, post holes are formed in the bed and bank so that the end of the post is 2 ft below maximum streambed scour (that portion of the streambed that is subject to movement). Hoag (1993) suggested that for bank stabilization, the cutting (post) should extend 2-3 ft above ground so as it leafs out, it can provide immediate bank erosion protection. He also recommended the cutting should be planted as much as 3-5 feet into the ground. If they are not this deep, moving water can erode around the cutting and rip it out of the ground. Roseboom places the posts four feet apart up the streambank. The posts in one row are offset from the posts in adjacent rows.

Both Roseboom (1993) and Hoag (1993) advised that willow posts should be long enough and placed deep enough to reach wet soil during dry summers. Hoag (1993) noted that plantings can occur at the water line, up the bank, and on top of bank in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table.

An excavator that is either fitted with a long, steel ram or an auger is typically required for installation. Roseboom (1993) reported that a steel ram on an excavator boom is more efficient at depths of 6 feet in clay soils. In contrast, an auger on an excavator boom forms deeper and longer lasting holes in stoney or sandy streambeds. The ram on the excavator is for creating a pilot hole in which to place the willow post. The willow post is fitted with a cap that goes over the post and then the heel of the bucket on the excavator is used to push the post down into the hole. Care must be taken to ensure that the post comes in contact with the soil so that no air pockets exist. In the case of the auger, this can be done by backfilling the sides of the hole in lifts and then tamping. In the case of the ram, the ram can be placed out a few inches from the post and run along the side of it into the soil so as to close the hole containing the post, especially toward the bottom of the hole.

Roseboom (1993) reported that in larger streams with non-cohesive sand banks, large cedar trees cabled to the willow posts along the toe of the bank can reduce toe erosion. The cedars not only reduce bank scour while root systems are growing, but retain moisture during drought periods. Another material used for the same purpose is a coir roll mentioned earlier. In addition to trapping sediment, the coir roll can be planted with either emergent aquatic vegetation or other willow cuttings. The cedar trees and the coir roll were used in combination with willow poles on Court Creek, Illinois, along a 600-ft reach. Figures 5.34 and 5.35 respectively illustrate work in progress and bank conditions four months after planting. Velocities were measured at this site during a major 1995 flood and ranged between 1.23 to 3.11 fps. They were measured at distances immediately in front of the treatment to 3.5 ft in front and at both the surface and 0.6 d. It is suspected that the willow contributed substantially to reduced velocities near the bank.

Hoag (1994a) and Hoag (1994b) provided specifications for and description of another type of implement that is used to make a pilot hole for the dormant willow post. It is called "The Stinger" and has been used by the USDA Natural Resources Conservation Service (NRCS) and the Bureau of Reclamation for establishing willow in riprapped revetments on shorelines of reservoirs and streambanks. According to Hoag (1994b), woody vegetation has been planted in rock rip-rap in the past, but the methods have concentrated on planting the cuttings first and dumping rock on top of them or planting through the rock riprap with a steel bar or water jet (Hoag 1994b cites Schultze and Wilcox 1985).

Hoag (1994b) states: "Neither of these methods are very efficient nor have achieved great success. 'The Stinger', however, builds upon these methods and utilizes the power of a backhoe to plant much bigger diameter and much longer cuttings than was possible before. "The Stinger" can plant cuttings right through rock riprap with minimal effort to better stabilize the rock, allow the cutting to be above the ice layer, and to improve the aesthetics of the riprap." "The Stinger" can plant through 2 to 3-ft riprap, but it must penetrate the moist soil below in which to push the dormant willow pole."

"The Stinger" was used on a bioengineering project on the upper Missouri River by the Omaha District, Corps of Engineers, in April 1996, to place dormant willow posts between and landward of large haybales used in the toe zone, as mentioned briefly above. "The Stinger" was used for efficiency and ease of construction (Figure 5.35).

There are constraints in using willow posts and several questions to be addressed in the process of planning if this method is considered. These are noted by Roseboom (1993), but have been modified here:

a. Does sunlight fall directly on the eroding bank? Willows must have at least partial sunlight to grow.

b. Is bedrock close to the surface? The soil should be at least 4-ft deep; this can be checked with a probe.

c. Are lenses of fine sand exposed in the eroding bank? If so, piping may be a problem and other methods of controlling piping need to be addressed for the dormant post method to be successful. This may be done through the brushmattress technique mentioned above in combination with a geotextile filter or it could be done by use of the vegetative geogrid technique mentioned above.

d. Is the stream channel stable upstream of the erosion site? If the stream cuts behind the upper end of willow posts, the entire bank will erode.

e. How deep is the stream along the eroding bank? Willow posts must penetrate to a depth that is deeper than the water near the eroding bank. There should be a shelf or at least a sloping bank that allows willow posts to penetrate at least 2 feet deeper than the deepest water at the shore or the posts will be undercut below the root zone. If this cannot be achieved by the willow posts, then some kind of hard toe, like a rock revetment, should be used to prevent scour beneath the posts. The length of the willow posts will depend on the water depth as well as the dryness of the soil above the stream level.

f. How wide is the stream channel at the erosion sites when compared to stable channels upstream and downstream? The channel with vegetation at the erosion site(s) should not be narrower than stable channels upstream or downstream; otherwise, vegetation could choke the channel and cause other erosion problems.

g. Do you have a source of large willows close to the site? Costs are less when willow stands are close because of less transportation costs. Also, there is less chance of mortality due to long durations of handling and possible drying of the willow.

h. Will the site be wet during dry summers? Willow posts require considerable water while the roots are becoming established from the root primordia on the stems. For dry sites, such as in the western states of the United States, tops of willow posts should be only 1-2 feet above ground and they should penetrate into at least the capillary zone of the groundwater table.

i. Can you keep cattle and other animals, domestic or wild, away from the posts during the first summer? Willows and other plants produce food for regrowth from leaf photosynthesis. If these sprouting branches with leaves continue to be browsed or if the tops of the plants continue to be cut off by beaver during the first growing season, they could die. It is best to prevent this by keeping cattle off of the area and either trap beaver off the area or spray the willow stems with organic beaver deterrent sprays, made with such constituents as mountain lion urine. It should be noted, however, that beaver damage during subsequent years of development may only promote resprouting of branches from the main stem and actually promote a shrubby-like plant. This is a positive effect from a surface roughness perspective whereas the many branches slow the current and promote sedimentation that can lead to other plant colonization.

j. Have debris jams or trees and logs forced floodwater into the eroding bank? These must be removed at least to the point where they are not directing water into a bank. Trees and logs can be moved parallel to the bank and cabled to dead men. Care should be taken, however, to ensure the upstream end is not flanked by currents, thus possibly jeopardizing that bank reach.

The dormant post method using willow provides a low-cost bank stabilization method with both wildlife and fisheries benefits. Roseboom (1993) reported that the method has received widespread support by both the agricultural and environmental communities: Farm Bureau, Soil and Water Conservation Districts, American Fisheries Society, and the Nature Conservancy. The willows hold the soil together long enough for other plants to become established on the bank through succession. Together, they provide a natural system of food and cover. More can be found on this method in the case study provided in Volume II.

Dormant Cuttings. Dormant cuttings, sometimes called "Live Stakes," involves the insertion and tamping of live, rootable cuttings into the ground or sometimes geotextile substrate. In higher velocity streams, such as over 5 fps, this method usually is applied in the splash zone with a combination of other methods, such as the brushmattress and root wad methods. Dormant cuttings can be used as live stakes in the brushmattress and wattling as opposed to or in combination with the wedge-shaped construction stakes previously mentioned. Or, they can be placed adjacent to the brushmattress. They can also be used in the matrix openings of the root wad logs along with root pads of other vegetative materials. If cuttings are used alone in the splash zone, the toe should be very stable and velocities should be less than 5 fps. Also, the soil in which they are placed should be fairly cohesive. Figures 36 a-c show an application of bankers (*Salix* X *cotteti)* and streamco (*S. purpurea* var. *nana)* willow cuttings that was installed on Irish creek in North Carolina by the NRCS. These willow were installed on a fairly cohesive bank on a staight reach with a stable toe.

Dormant cuttings can vary in size, but are usually a minimum of 1/2 inch in diameter at the basal end (Hoag, 1994b). Cuttings can be used that are up to 2 to 3 inches in diameter and have been noted by Hoag (1993) to have the highest survival rates. Cutting length is largely determined by the depth to the mid-summer water table and erosive force of the stream at the planting site (Hoag 1993). Plantings can occur at the water line as in the splash zone, up the bank into the bank zone, and on top of the bank (terrace zone) in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table (Hoag 1993).

Cuttings should have their side branches cleanly removed and the bark intact so that the cutting is one single stem. Care should be taken to make clean cuts at the top and the bottom so that the bark is not separated from the underlying woody tissue. Also, be sure they are cut so that a terminal bud scar is within 1 to 4 inches of the top because cuttings put out their greatest concentration of shoots and their strongest ones just below an annual ring (formed from a terminal bud scar). At least two buds and/or bud scars should be above the ground after planting (Gray and Leiser, 1982). Tops are normally cut off square so they can be tamped or pushed easily into the substrate. The basal ends are often angled for easy insertion into the soil. When selecting material from a natural stand, care should be taken to see that the harvest material is free from insect damage, disease, and splitting.

Root pads are clumps of shrubbery composed of such species as willow (shrubby forms), redosier dogwood, european alder (*Alnus glutinosa*), and others. It is often used in the splash zone as a part of root wads where the root pads are positioned in between them. Root pads can also be used further up the slope into the bank and terrace zones. Caution should be exercised in planting these during the dormant season. They can be removed from harvest areas and placed at the project site with front-end loaders. "Veimeer" type spades are sometimes used on root pads where species have deep penetrating roots whereas front-end loaders are used on species whose roots spread out more at the surface. Placement of root pads on slopes greater than 1V:6H should include securing the root pads by driving 2-in diameter, 18 to 24-in long wooden stakes through the pads at 2 to 3-ft intervals (Logan et al., 1979)

Bank Zone

This zone may be exposed to considerable flooding and current and wave action. If only mild current and wave action is expected, sodding of flood-tolerant grasses like reed canagry grass, buffalo grass (*Buchloe dactyloides*), or switchgrass (*Panicum virgatum*) can be employed to provide rapid bank stabilization. Usually, the sod must be held in place with some kind of wire mesh, geotextile mesh such as a coir blanket, or stakes. A soilless system for growing wetland plants in coconut fiber mats (coir mats) was discussed above for the splash zone and can be extended up into this zone as well.

Instead of using sod in this zone, the California Department of Parks used seed from wetland plants, such as various sedges and grasses, in combination with burlap and a coir woven fabric (0.8 lbs/sq yd) laid over the seed (Figure 5.37). This whole system was placed in the bank zone above root wads and willow clumps that were installed in the toe and splash zones, respectively. The combination of root wads, willow clumps, and this seeding and burlap/coir combination was stable in most reaches where it was installed although vegetative cover from the planted seed was less than expected.

To augment the sodding practice for this milder energy regime, shrub-like willow, dogwood, and alder transplants or 1 year-old rooted cuttings are effectively used in this zone (Edminster et al. 1949; Edminster 1949; and Seibert 1968). These transplants or cuttings should be planted about 0.5 m apart and in rows. Further planting practices can be found in Edminster et al. (1949) and Edminster (1949). Newly planted banks are usually subject to additional erosion and the shrub plantings should have mulch placed over them to serve as temporary protection. Mulch of woody plant branches are best for this and should be the heaviest on outside curves of the stream where the current strikes the bank. The mulch should be tied down with chicken wire or wire laced between stakes since the mulch may float away when flooded (Edminster 1949).

Where severe erosion is expected and currents on the bank are expected to exceed 8 fps, methods such as the brushmattress discussed for the splash zone above should be carried up into the bank zone. Additionally, two other methods using woody materials are appropriate for this zone. They include contour wattling and brush layering.

Contour Wattling. Contour wattling was discussed above as an integral component of the brushmattress. In the bank zone, and in this context, it may be used independent of the brushmattress along contours. Sometimes, you will see the term "fascine" in lieu of the term wattling. They are buried across the slope, parallel or nearly parallel to the stream course, and supported on the downhill side by stakes (Figures 38 a-b). They also have stakes driven through the bundles and can be either living or constructed from wood as previously described. The sprouting attributes of the brush species used, such as willow, combined with the supportive attributes of the structure itself provide an integrated system of stems, roots, wire, and stakes that hold the soil in place. When used on slopes, they protect against erosion caused by downward water flow, wind action, trampling caused by wildlife and livestock, and the forces of gravity. Further descriptions of wattling (fascine) construction can be found in Edminster (1949), Schiechtl (1980), Gray and Leiser (1982), Allen and Klimas (1986), Coppin and Richards (1990), and Georgia Soil and Water Conservation (1993).

Contour wattles (fascines) are often installed in combination with a coir fiber blanket over seed and a straw mulch. In this way, slopes between the wattles may be held firmly in place without development of rills or gullies. Figure 5.39 illustrates this and was prepared by Robbin B. Sotir and Associates for the Corps of Engineers Nashville District and successfully used on the Tennessee River near Knoxville, Tennessee. It should be noted that there was significant toe protection in the toe zone with rock riprap; however, there was also overbank flooding shortly after installation of the contour wattles and the treatment was stable.

Brush layering. Brush layering can be used in the bank zone as it was in the splash zone except with some modifications. Geotextile fabrics, such as coir woven fabrics, should be used between the layers and keyed into each branch layer trench, so that unraveling of the bank does not occur between the layers (Figure 5.40). Before the geotextile fabric is applied, the areas between the branch layers should be seeded with flood-tolerant grasses or grass-like plants, like sedges, and then covered with a straw mulch. This method was used to stabilize levees in low-lying areas of fen districts in England (from Gray and Leiser, 1982 who cited Doran, 1948). Slope heights, the vertical distance between the layers, should not exceed 3 times the length of the longest brush in the trench. This would be similar in principle to a sloping reinforced earth revetment (from Gray and Leiser, 1982 who cited Bartos, 1979) where metal strips are placed essentially horizontally in successive layers up the face of a slope. In a reinforced earth revetment it is common practice to make the strip length (or width of reinforced volume) about one-third the slope height (Gray and Leiser, 1982).

Brush layering lends itself to partial mechanization because the benches can be excavated with a small backhoe or grader. Regular construction equipment, such as a front-end loader with a clasp on the bucket, can be used for hauling and placing the brush. Backhoes or similar equipment can also backfill.

The choice between wattling and brush layering, according to Gray and Leiser (1982), should be based on economics, the potential stability of the fill (in this case, stability of the streambank), and the availability of suitable plant materials. Generally speaking, brush layering is considered to be less expensive than contour wattling. Brush layering stabilizes a fill or bank to greater depths, but more plant material is required than for contour wattling. However, if the streambank is disturbed to the extent that rebuilding and reshaping is necessary, brush layering may be the better alternative, because of its ability to stabilize a bank to greater depths.

Again, as it was in the earlier parts of this report, emphasis should be placed on prevention of flanking of the bioengineering treatment. In this case, either contour wattling or brush layering treatments should be protected with some kind of hard structure both upstream and downstream of the treatment. If natural hard points, such as large boulders, rock outcroppings, or hard geological strata, are not present, then one should consider use of a rock refusal. This would be rock riprap that starts at the bottom of the bank, continues up the bank, and is keyed into the bank.

Terrace Zone

This zone, as mentioned earlier, is rarely flooded and usually not subjected to erosive action of the stream except during occasional flooding. When flooded, it receives overbank flooding with return flows that can cause gullying and rilling to occur on the fall of the hydrograph. It is in this zone that vegetation is needed with deeply penetrating roots to hold the bank together, such as larger flood-tolerant trees. Grasses, other herbs, and shrubs can be planted in between the trees, depending on their shade tolerance. Bioengineering, per se, is not normally used in this zone unless there are deep gullies that have occurred as a result of return flows or slopes still occur in this zone that are 3H:1V or greater. In these cases, branch layering or contour wattling treatments are often employed across the gully or on the contours of the slope.

Care should be taken in using large trees in this zone. They should be planted far enough back from the bank that their shade does not kill out the vegetation in the splash and bank zones. Narrow channels, especially, can be completely shaded from one side. When trees are planted in this zone, they are planted either as container-grown (potted) or bare-root plants. Suggestions vary on the size of container-grown plants. Leiser (1994) suggests using containers with a minimum size of 9 cubic inches with a depth of 8 inches and a maximum size of no larger than one quart milk carton. Plants in larger containers increase the cost for purchase and planting substantially. Survival is frequently reduced because of limited root systems in relation to size of the tops of the plants (Leiser, 1994). The important thing to remember is to have a container with growing medium well filled with roots so that the roots and medium form a cohesive unit when removed from the container.

Woody materials (Hoag 1994b), whether they be grown in containers or derived from cuttings, should be used only in the bank and terrace zones when the following conditions exist:

a. where long periods of inundation or water erosion are minimized;

b. where adequate moisture is available, i.e., natural precipitation is adequate for species selected or plants are irrigated;

c. where there is no competing vegetation or a 30" diameter area around plant is scalped of competing vegetation at planting time;

d. where plants have a low risk of physically being pulled or eroded out due to shallow rooting system during the first year after being planted.

Hydroseeding and hydromulching can be a useful and effective means of direct seeding in the terrace zone, particularly on slopes greater than 3H:1V and places where it is difficult to get equipment. Sometimes, it is possible to work from a small barge and use hydroseeding and hydromulching equipment on the barge (Figure 5.41) and blow them onto the bank. If seeds are blown on in a water slurry, a generic type mix is suggested by Leiser (1994):

Grass seed	50 pounds/acre
Woodfiber mulch	500 pounds/acre
Water	As needed
Fertilizer (if not broadcast)	250 pounds/acre

According to Leiser (1994), the slurry should be continuously mixed as ingredients are added and mixed at least five minutes following the addition of the last ingredients before application begins. The slurry should be continuously mixed until used and application must be completed within two hours of the last addition. Water should be potable or at least filtered so as not to clog spraying equipment. The slurry should be applied at a rate that is non-erosive and minimizes runoff.

On level areas and slopes of less than 3H:1V, seed should be broadcast by mechanical hand or power-operated spreaders or drilled on contour with a Brillion or range drill as site conditions permit. Broadcasted seed should be covered by raking or dragging with a chain, chainlink fence, or other approved means unless previously planted with cuttings or transplants (Leiser, 1994).

Sometimes surface drainage water intercepts the terrace zone from inland areas and can cause gullying not only in the terrace zone, but in the other zones on the bank. This water should be diverted or controlled with a small furrow or trench at the top of the bank. This trench should be sodded to prevent erosion.

Limitations/Cautions

Intervention into stream corridors should be done on a selective basis. Projects located within relatively healthy systems are more likely to be successful, and it is often beneficial to prevent the decline of these healthier systems while an opportunity remains to preserve their biological diversity. Rehabilitation of highly degraded systems is also important, but these systems often require substantial investment of resources and may be so modified that partial success is often a realistic goal.

As a first priority, consider those measures that are self sustaining or reduce requirements for future human support; use native, living materials for restoration; restore the physical, biological, and chemical functions and values of streams or shorelines; improve water quality through reduction of temperature and chronic sedimentation problems; provide opportunities to connect fragmented riparian areas; and retain or enhance the stream corridor or shoreline system.

Using planted vegetation for streambank erosion control also has limitations. These may include its occasional failure to grow; it is subject to undermining; it may be uprooted by wind, water, and the freezing and thawing of ice; wildlife or livestock may feed upon and depredate it; and it may require some maintenance. Most of these limitations, such as undermining, uprooting by freezing and thawing, etc., can often be lessened or prevented by use of bioengineering measures.

Buffer Strips and Setbacks

As urban areas expand, regions previously unaffected by development are now in need of strategies for protection and restoration of existing riparian forest ecosystems to maintain or improve water quality. Urban planning should consider riparian forests ecosystems with management strategies developed as an integral part of the community plan. Two effective management strategies are buffers and setbacks.

Buffer zones are strips of vegetation, either natural or planted, around water bodies. Such vegetated zones help reduce the impact of runoff by trapping sediment and sediment-bound pollutants, encouraging infiltration, and by slowing and spreading stormwater flows over a wide area. They also help stabilize streambanks, reduce water temperatures, provide habitat for a number of wildlife species, and are an important landscape feature from an aesthetic perspective.

Setbacks are restrictions through zoning or other mechanisms on development activities within a specified distance of a stream or other water resource. They can prevent or minimize erosion and gully formation, thus minimizing sedimentation and associated nutrient enrichment downstream. Easements can be created within setback zones to provide an alternative method of gaining control of strategic land. Easements may be negotiated or purchased from landowners and passed on to future owners as part of the deed to the property. These "green belts" around waterways can be used to protect the water and also provide parks and recreational areas for residents. The popularity of setbacks and easements in urban environments is growing rapidly as planners and residents alike recognize their benefits to property values and quality of life.

To create effective riparian buffers strips land use planners and design professionals must understand the functions of riparian ecosystems and recognized that riparian strips can not be relied upon as complete buffers for the detrimental effects that can be caused by upland development. Upland activities and development must be designed and managed so that they will not overburden the moderating effects of buffer strips. Buffer zones, setbacks, and easements are most effective when used as part of a BMP system including measures to reduce stormwater flows from upgradient development and measures to directly repair eroded streambanks and restore existing damage to streams.

When employed in conjunction with other management practices such as stormwater detention and stream restoration, buffer strips can:

- Provide shade that reduces water temperature
- Cause deposition of sediments and other contaminants
- Reduce nutrient loads of streams
- Stabilize streambanks with vegetation
- Reduce erosion caused by uncontrolled runoff
- Provide riparian wildlife habitat
- Protect fish habitat
- Maintain aquatic food webs

- Provide a visually appealing greenbelt
- Provide recreational opportunities

Existing Buffer Zone Guidelines

Although their value is well recognized, criteria for buffer strip sizing is not well established. Economic and legal considerations have taken precedence over ecological factors in many cases, and most existing criteria address contaminant and nutrient loading. In general, the width and vegetation composition of buffer strips will dictate the extent to which the above benefits will be realized. Some benefits can be obtained for buffers as narrow as 10 feet while others require thousands of feet. In general, the ability of buffer strips to meet specific objectives is a function of the vegetation species utilized and their density, buffer width and length, the slope, and the position in the landscape. Buffer width guidelines from the literature are summarized in Table 5.1.

Table 5.1 General buffer width guidelines

Function	*Description*	*Recommended Width*[1]
Water Quality Protection	Buffers, especially dense grassy buffers on gradual slopes intercept overland runoff, trap sediments, remove pollutants, and promote ground water recharge.	20 – 100 ft.
Riparian Habitat	Buffers, particularly diverse stands of shrubs and trees, provide food and shelter for a wide variety of riparian and aquatic wildlife.	30 – 300[2] ft.
Stream Stabilization	Riparian vegetation moderates soil moisture conditions in stream banks, and roots provide tensile strength to the soil matrix, enhancing bank stability.	30 – 50 ft.
Flood Attenuation	Riparian buffers promote floodplain storage due to backwater effects, they intercept overland flow and increase travel time, resulting in reduced flood peaks.	50 – 500 ft.
Detrital Input	Leaves, twigs and branches that fall from riparian forest canopies into the stream are an important source of nutrients and habitat.	10 – 30 ft.

1 - Synopsis of values reported in the literature.

2 - A few wildlife species require much wider riparian corridors.

In order to ease the task of developing a new design for each buffer application, we present general width and vegetation design guidelines that we think can be used in most urban situations with acceptable results. This multi-purpose design can be used "as is" or adjusted to better suit specific project needs or site conditions.

General Design

The buffer width, as defined herein, is measured from the top of the bank or level of bankfull discharge. Riparian buffers will vary in character and size based on environmental setting, proposed management, level of protection desired and objectives. The buffer composition will include a diversity of native, non-invasive woody trees and shrubs (multiple species including hardwoods) as well as warm- and/or cool- season grasses. Newly established buffers will be managed to allow the establishment of an organic duff layer and understory vegetation.

The NRCS standard guidance on buffers provides for variable widths from 35-100'. For urban lands, we recommend an additional grass filter strip (of 15 feet or greater up slope) to improve and sustain pollutant removal performance. "Buffer averaging," the practice of expanding and contracting buffer widths in order to account for stream channel meandering, property lines and infrastructure, and efficiency of protection measures, is acceptable. We recommend that the minimum required buffer width for streams in urban environments be 35 ft. A conservation width of at least 100 ft on each side is also recommended for rentention of existing riparian forests.

In all cases, buffer widths of 50 ft or wider should be promoted as the appropriate width for optimizing a range of multiple objectives for water quality and fish habitat improvement. Increasing widths to encompass the geomorphic floodplain is likewise desirable in order to optimize flood reduction benefits. Widths of up to 300 ft may be needed to ensure values related to some wildlife habitat and use as migration corridors.

A three-zone riparian buffer concept is recommended to assist with planning, design and long-term management. The width of each zone is determined by site conditions and objectives, as discussed below.

Zone 1 - Beginning at stream edge, Zone 1 functions as an extension of the stream or water body and is the area in which critical habitat and stream integrity objectives are achieved. Shade, detritus and large woody debris are provided by mature forest vegetation. Vegetation in this zone helps reduce flood effects, stabilize streambanks and remove some nutrients. Composition of the vegetation in this zone should be native, non-invasive trees and shrubs of a density that permits understory growth. The minimum width of Zone 1 is 10 ft.

Zone 2 - Target vegetation in this zone is a managed riparian forest with a vegettion composition and character similar to natural riparian forests in the region. Extending upslope from Zone 1 for a minimum of 10 ft, function of Zone 2 is to remove sediments, nutrients and other pollutants from surface and groundwater. This zone provides most of the enhanced habitat benefits, allows for recreation benefits, and helps reinforce Zone 1.

Zone 3 – Zone 3 is provided to slow runoff, infiltrate water and filter sediment and its associated chemicals. It is the zone that provides the greatest water quality benefits. Zone 3 may contain grass filter strips, level spreaders or other features. Protects Zone 1 and 2. The minimum width of Zone 3 is 15 ft.

An example of a general, multi-purpose, riparian buffer design might consist of a 50 ft-wide strip of grass, shrubs, and trees between the normal bank-full water level and adjacent lands. Trees spaced 6-10 ft apart occupy the first 20 ft nearest the stream, shrubs spaced 3-6 ft apart dominate the next 10 ft, and grass extends 20 ft further out. This design can be thought of as consisting of 2 rows of trees and 2 rows of shrubs that together constitute Zones 1 and 2, and 20 ft of grass in Zone 3. Planting trees and shrubs in well-spaced rows make maintenance activities, such as mowing or mulching, much easier. Care should be taken to offset the rows of trees and shrubs so as to form a diamond pattern. This design requires approximately 6 acres per mile of bank (12 acres per mile of stream if installed on both sides of the stream), not counting any setbacks or easements.

This buffer design provides modest levels of most buffer benefits, with the wildlife habitat for a few species perhaps not met. Trees and shrubs near the waterway stabilize the bank, improve and protect the aquatic environment, and protect adjacent land from flood erosion and debris damage. Grass disperses and slows the flow of adjacent runoff which promotes settling of sediment and infiltration of nutrients and pesticides, while vigorously growing vegetation and soil microbes take up nutrients and some pesticides. Perennial vegetation provides wildlife habitat and visual diversity to an urban landscape.

Adjustments

The general design described above provides a useful starting point for developing more efficient buffer designs. Possible adjustments to the general design and the rational for doing so are presented in Table 5.2.

Table 5.2 Buffer Adjustments

Rational	*Adjustment*
Reducing buffer costs	Narrower buffer. The landowner should expect less overall benefit from a narrower buffer, particularly for nutrient and pesticide runoff control and for wildlife habitat. In general, however, a narrow buffer provides more benefits than no buffer at all. Narrower buffers require more careful selection of vegetation types in order to maximize benefits. As needed. Federal, state, and privately supported incentive programs for conservation, forestry, or alternative products will vary in their requirements for vegetation type, minimum width, and management. Often, such programs require a greater land area than is provided by a 50-ft buffer width.
Increasing overall buffer benefit	Wider buffer. This applies mainly to nutrient and pesticide runoff control and wildlife habitat. Such an adjustment may also better accommodate recreation features in the floodplain or riparian zone. Be aware that there may be decreasing added benefit for each additional unit of width, such as is commonly observed for sediment filtration. Acceptable width for aesthetic benefits, such as visual diversity, is entirely a matter of the landowner's opinion.

Site conditions where some benefits are not needed	For ephemeral streams with negligible aquatic resources, trees and shrubs are not needed for providing shade, shelter, and plant litter. For warm-water fisheries, trees and shrubs may not be needed for shade and temperature control, unless there remains a need to control algae blooms. Trees and shrubs may still be required for providing debris for shelter and food.
Emphasizing one benefit (high-priority) over others (lower priority)	To emphasize bank stabilization place a greater proportion of the buffer width in shrubs and trees. On smaller streams and lakes, a narrower buffer may be sufficient. Where active erosion is occurring, flood-tolerant woody plants, such as willows, may be planted at the water's edge. Severe bank erosion may require intensive engineering. To emphasize filtering sediment from agricultural runoff, use a narrower buffer with the greatest proportion of width in grass. Dense, stiff grasses may perform better than bunchgrasses and short, flexible grasses. To emphasize nutrient and pesticide runoff control, particularly of soluble forms, a wider buffer and greater proportion in fast-growing grasses and trees are needed. Deep-rooted grasses may perform better than shallow-rooted grasses. To emphasize habitat for larger forest animals, a wider buffer is needed, with a greater proportion of width in shrubs and trees. More variety of plant species provides habitat for a greater diversity of animals. To avoid tree windthrow which can damage stream banks and add excessive amounts of large debris to the waterway, substitute shrubs for trees, or reverse tree and shrub positions in the buffer design, i.e., shrubs near bank, trees in the middle. Use deep-rooted, wind-firm tree and shrub species. This adjustment may be useful on wide, steep streambanks. To emphasize protection from flood damage to adjacent lands and structures, a greater proportion of the buffer should incorporate flood-tolerant trees and shrubs. Larger streams and rivers may require greater overall buffer width.

FIGURE 5.1 EROSION PROBLEMS RELATED TO HUMAN ACTIVITY

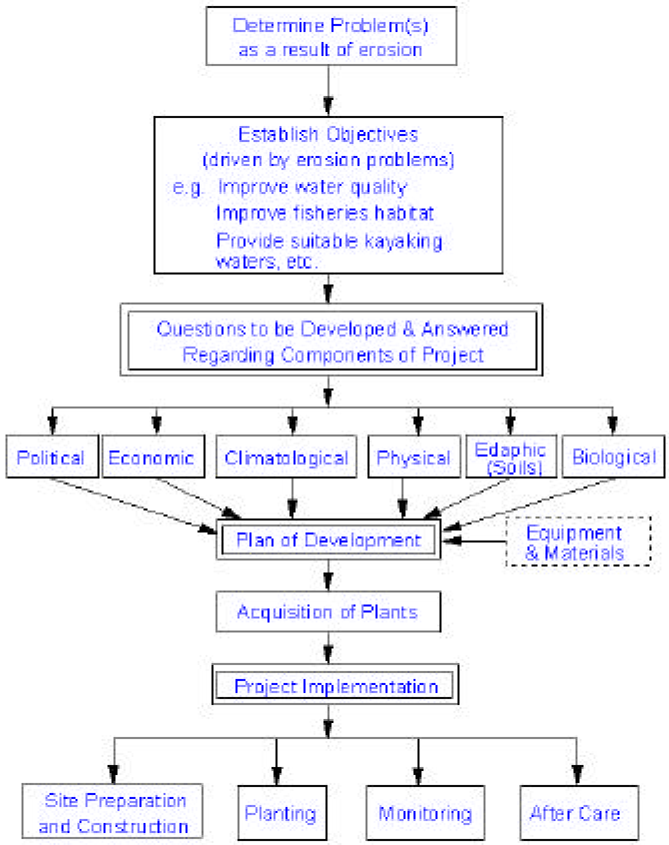


FIGURE 5.2 CRIBS SERVING AS DEFLECTION STRUCTURES

FIGURE 5.3 ROCK RIPRAP

FIGURE 5.4 STONE TOE SECTION

FIGURE 5.5 GABION STRUCTURE

FIGURE 5.6 STONE SPUR

FIGURE 5.7 ROCK TOE

FIGURE 5.8 ROCK TOE WITH HAY BALE CYLINDERS

FIGURE 5.9 ROCK TOE WITH HAY BALE CYLINDERS

FIGURE 5.10 ROCK ROLL

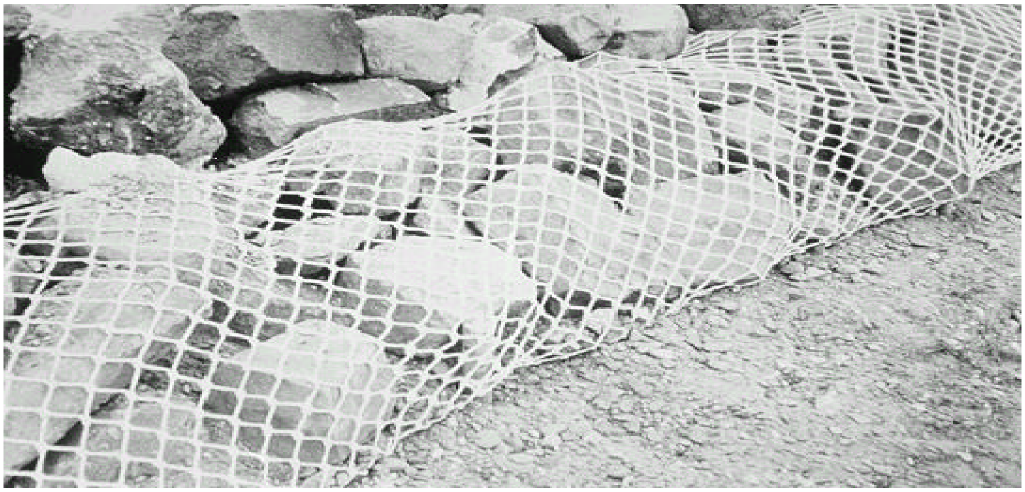


FIGURE 5.11 LARGE ROCK TRANSVERSE DIKES

FIGURE 5.1 2 GABION MATTRESSES

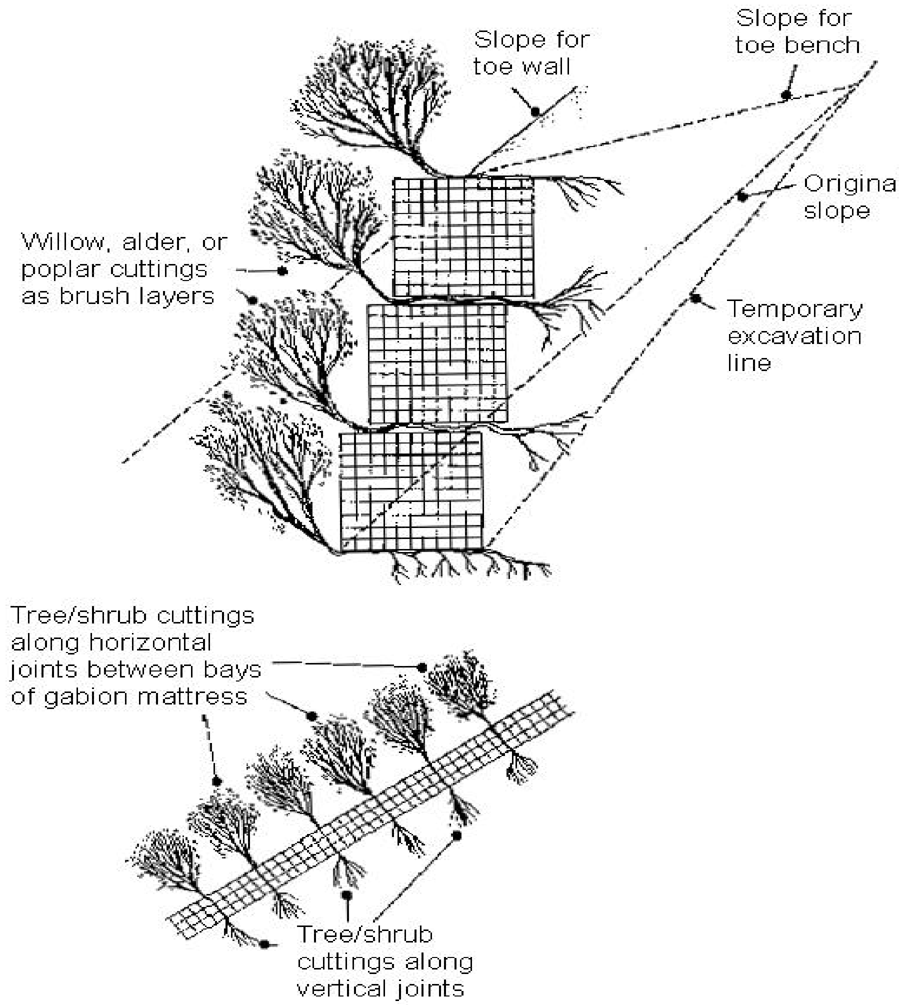
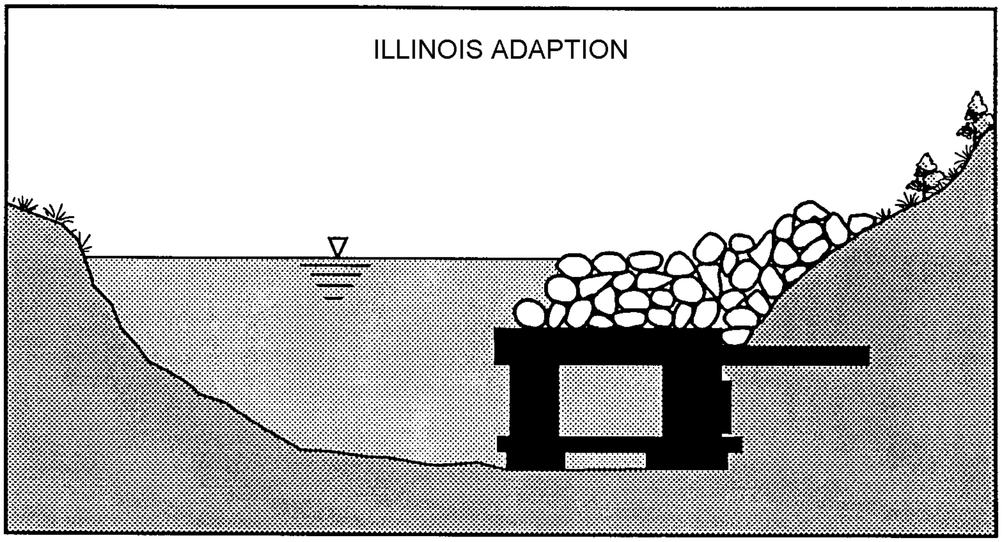


FIGURE 5.13 LUNKERS



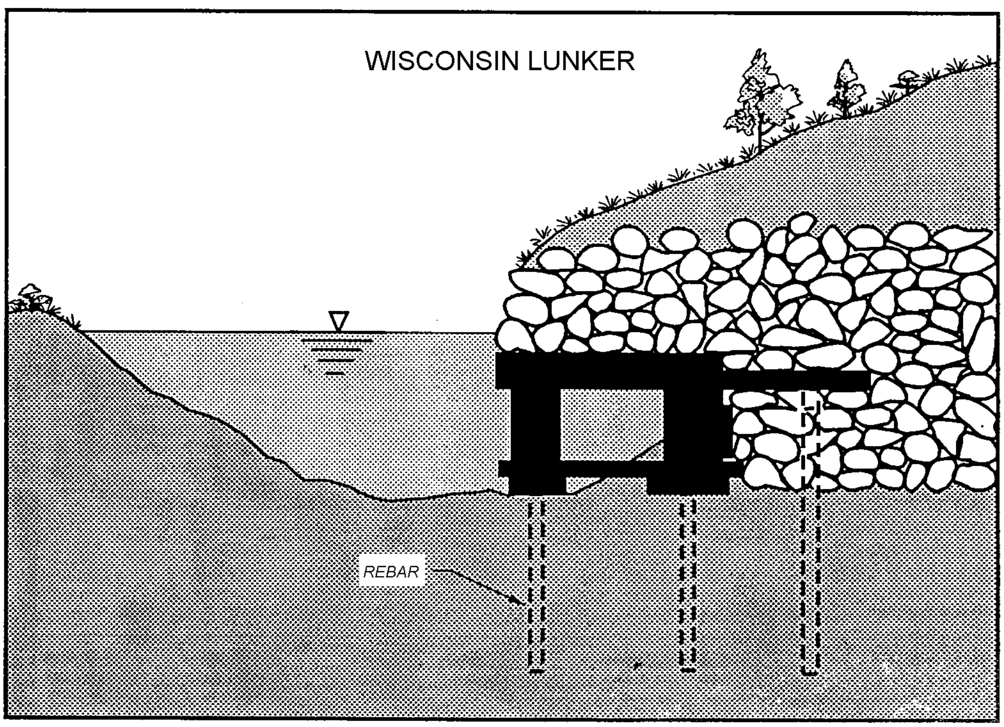


FIGURE 5.14 BANK CRIB WITH COVER LOGS

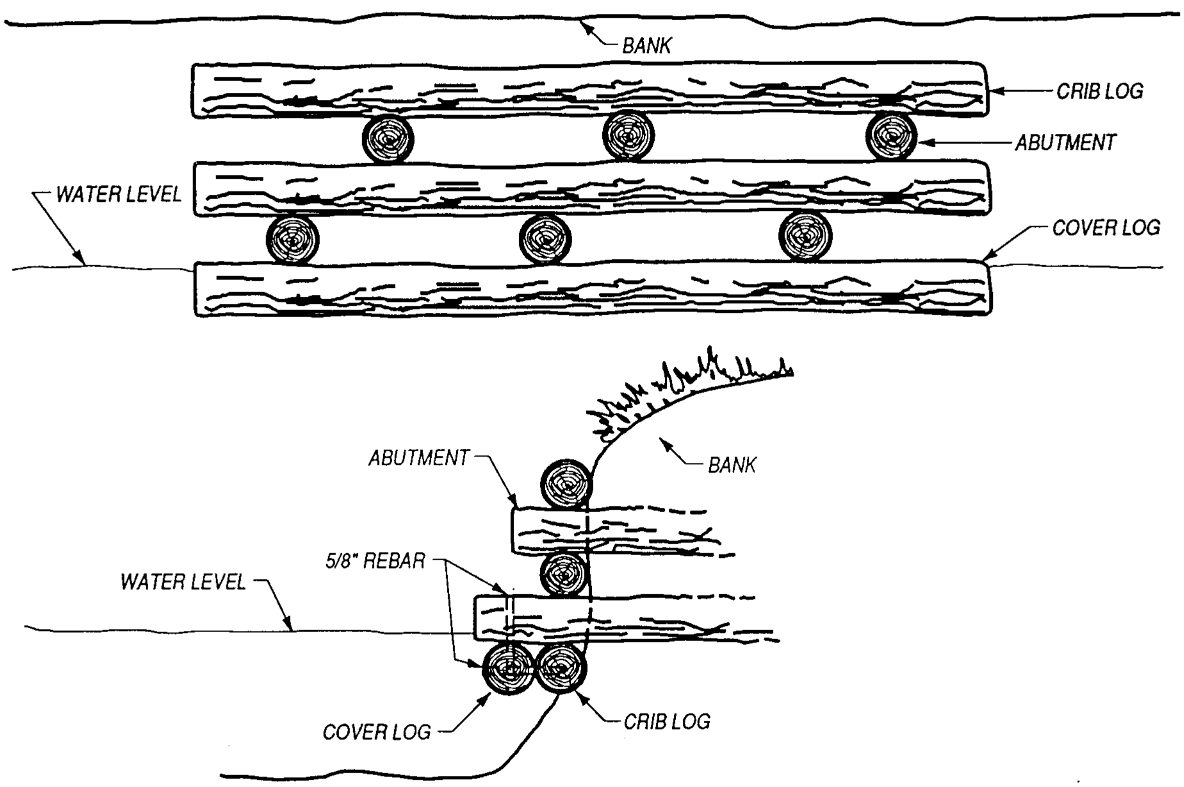


FIGURE 5.15 LOG REVETMENT

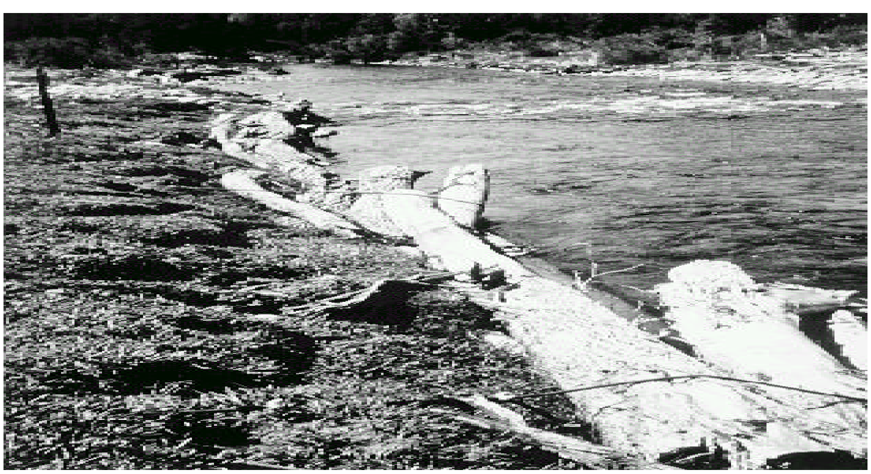


FIGURE 5.16 SCHEMATIC OF A LOG REVETMENT

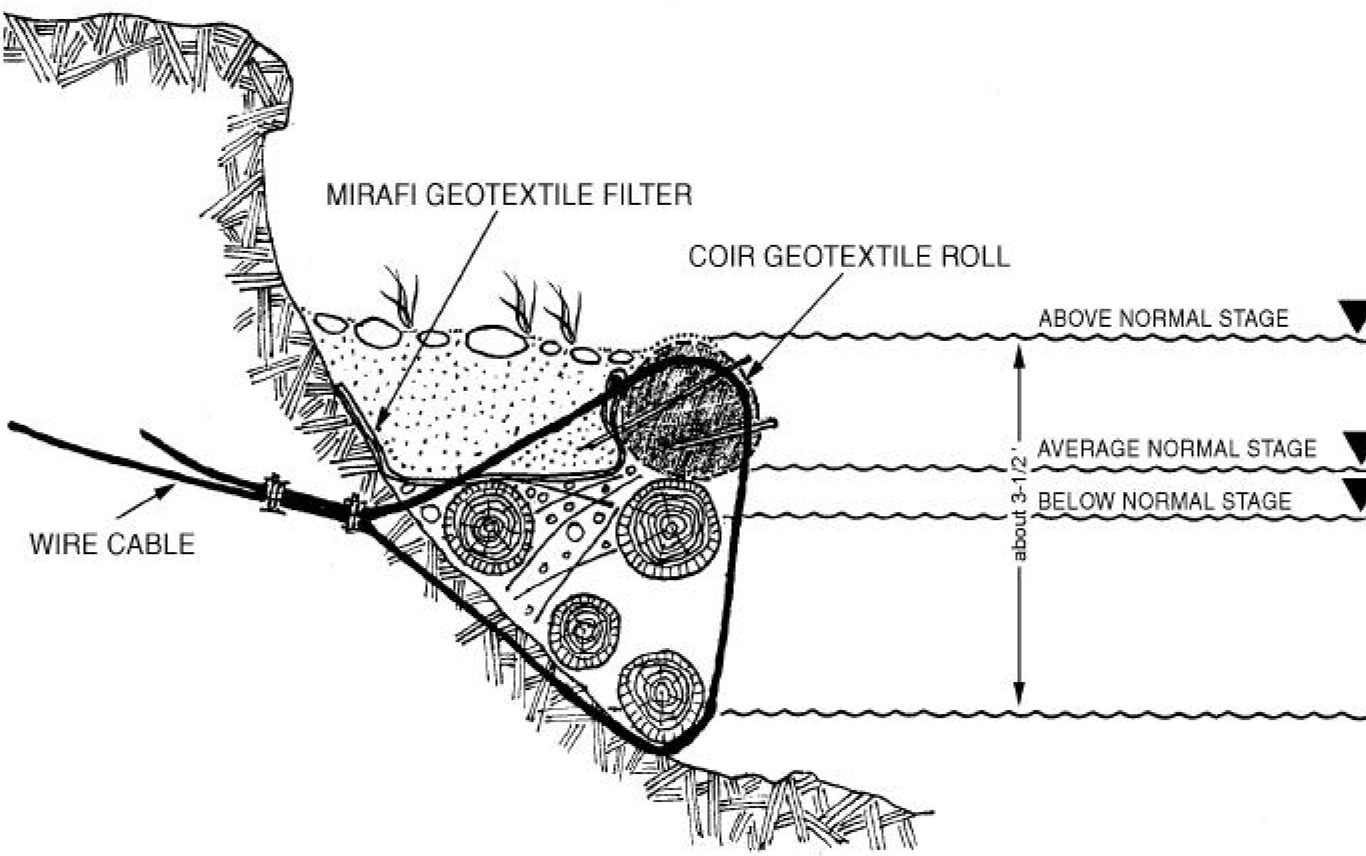


FIGURE 5.17 INSTALLED LOG REVETMENT

FIGURE 5.18 ROOT WADS

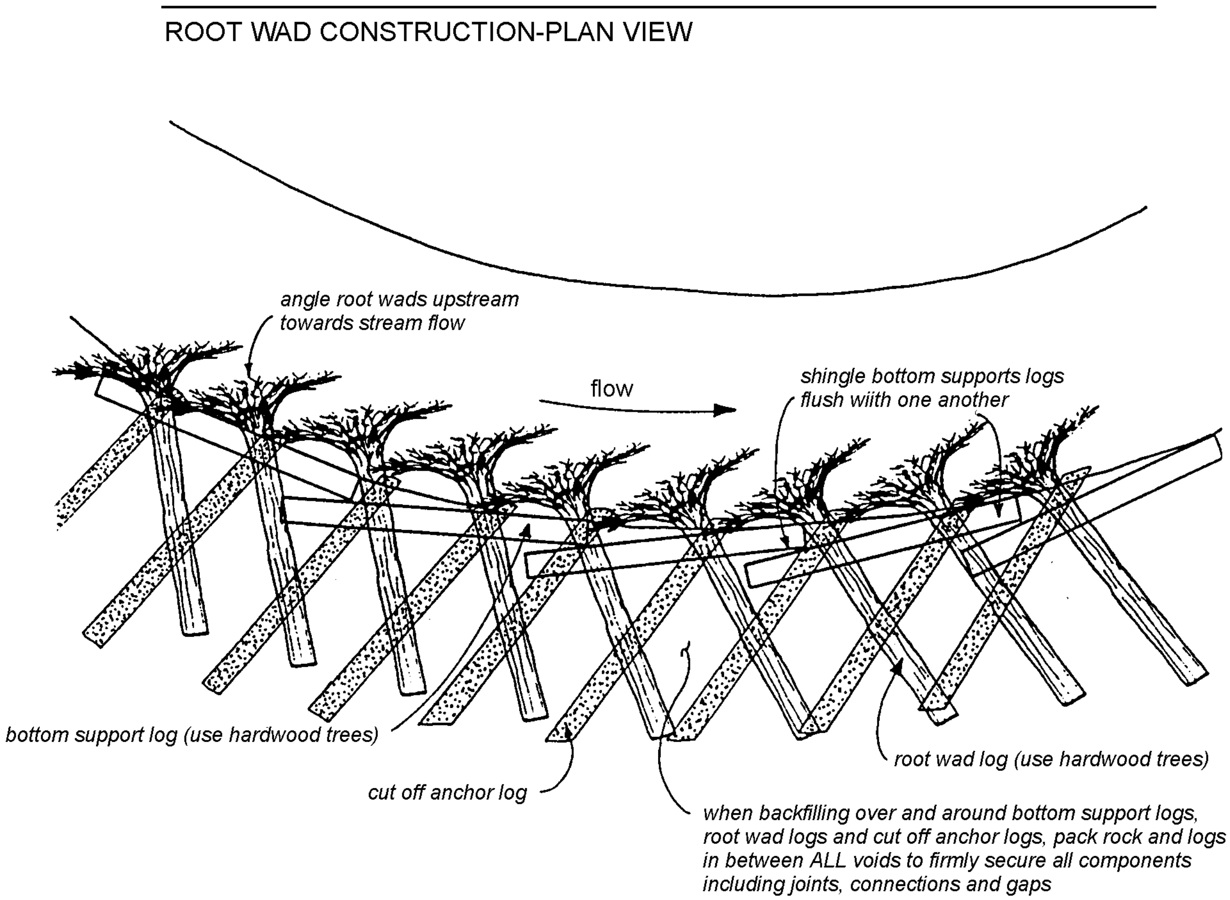


FIGURE 5.19 TREATMENT USING ROOT WADS

FIGURE 5.20 SCHEMATIC OF COIR GEOTEXTILE ROLL

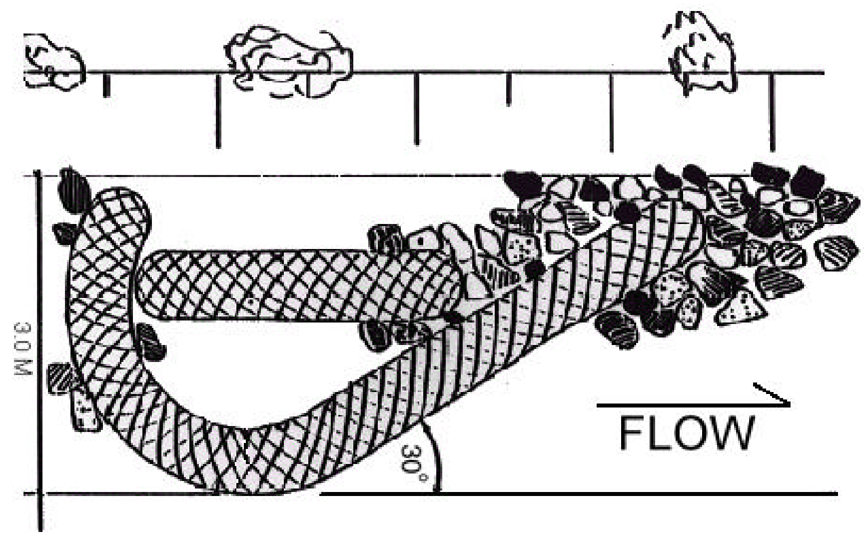


FIGURE 5.21 SEVERAL COIR ROLLS INSTALLED

FIGURE 5.22 SCHEMATIC OF COIR ROLL

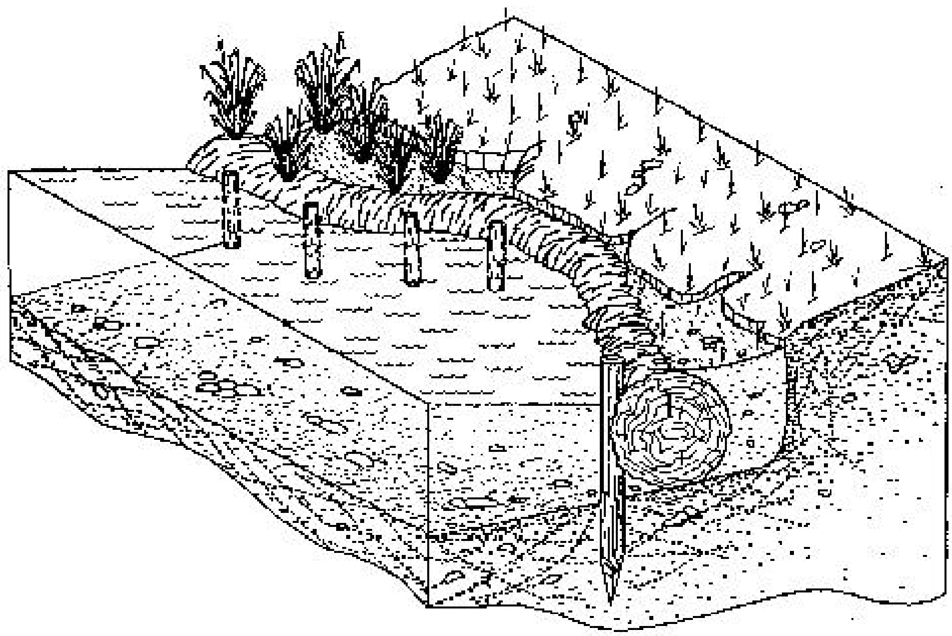


FIGURE 5.23A COIR ROLL WITH VEGETATION

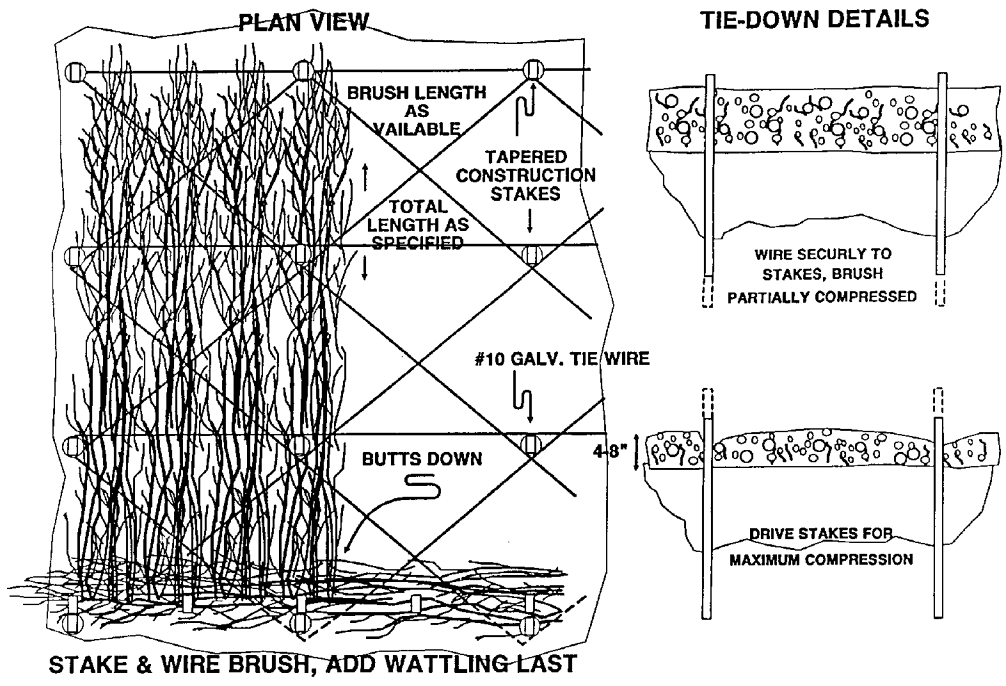
FIGURE 5.23B COIR ROLL WITH VEGETATION

FIGURE 5.23C COIR ROLL WITH VEGETATION

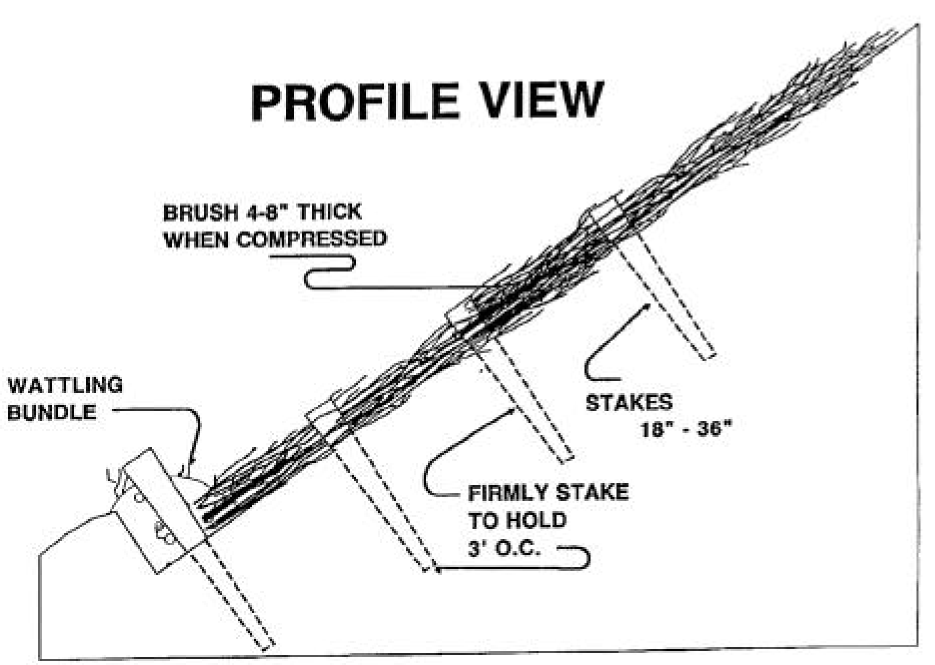
5.24A COIR FIBER MATS

5.24B COIR FIBER MATS

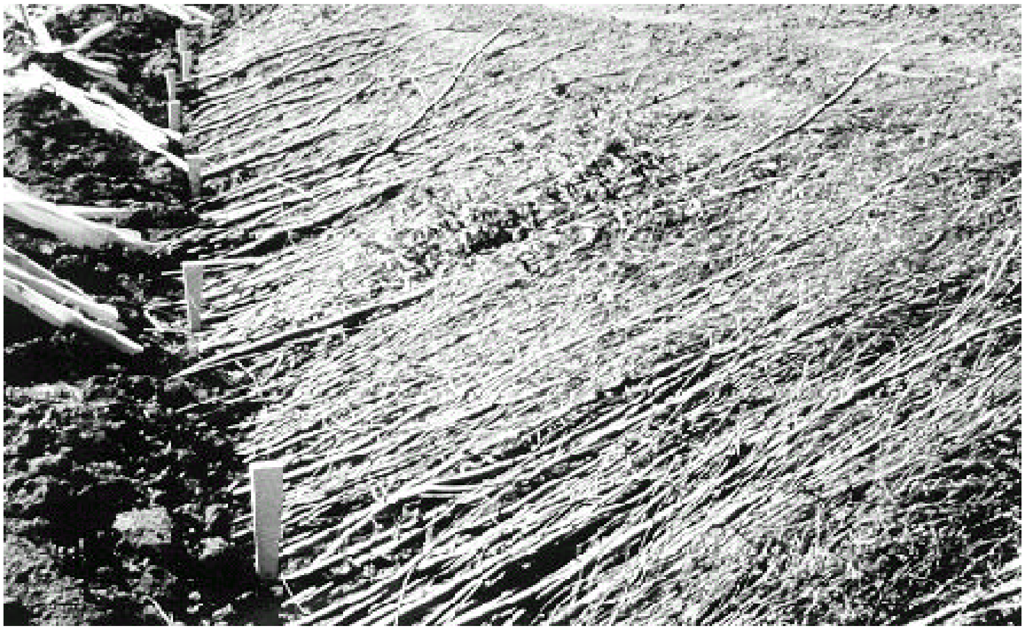
5.25A SCHEMATIC OF A BRUSHMATTRESS AND WATTLING



5.25B SCHEMATIC OF A BRUSHMATTRESS AND WATTLING



5.26A INSTALLING A BRUSHMATTRESS AND WATTLING



5.26B INSTALLING A BRUSHMATTRESS AND WATTLING

5.26C INSTALLING A BRUSHMATTRESS AND WATTLING

5.27 SCHEMATIC OF BRANCHES PLACED ON LIFTS

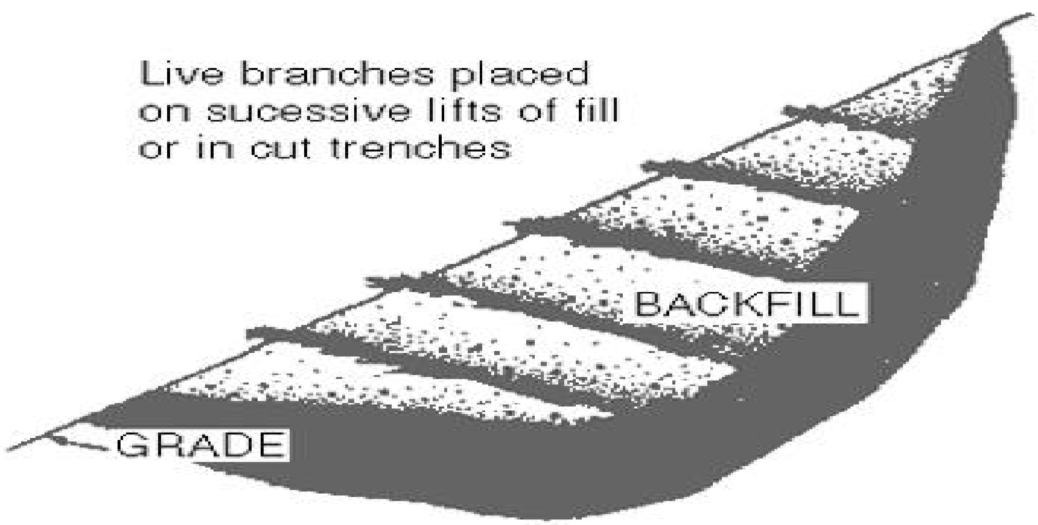


FIGURE 5.28 COVERING BRUSH LAYERS IMMEDIATELY

FIGURE 5.29 BRUSH LAYING OR BRANCH PACKING COMPLETED

FIGURE 5.30 FABRIC ENCAPSULATED SOIL SYSTEM

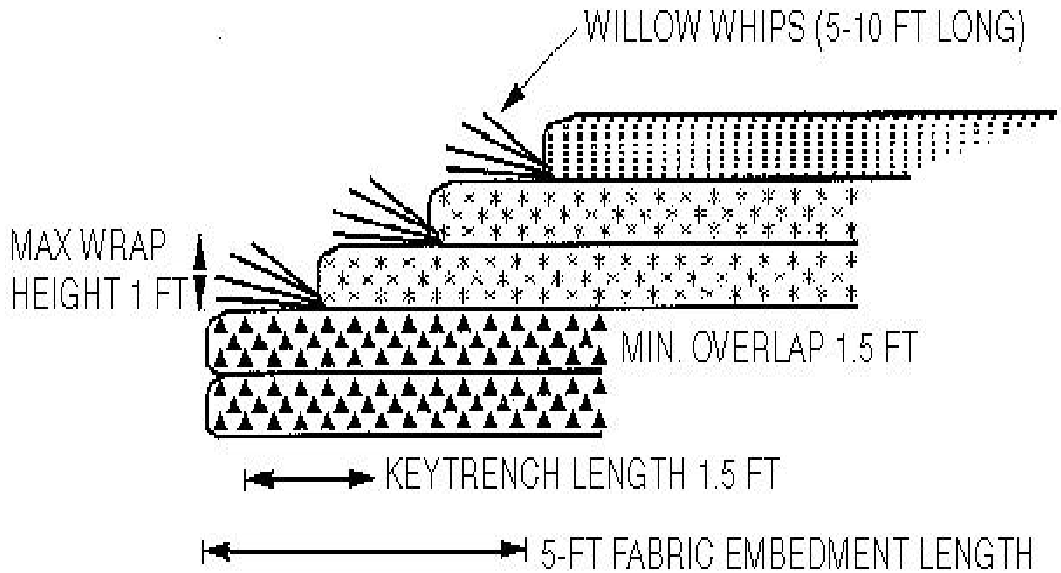


FIGURE 5.31 UPPER TRUCKER RIVER SITE BEFORE CONSTRUCTION

FIGURE 5.32 UPPER TRUCKER RIVER SITE AFTER CONSTRUCTION

FIGURE 5.33 WORK IN PROGRESS

FIGURE 5.34 COMPLETION OF WORK 4 MONTHS LATER

FIGURE 5.35 BACKHOE DIGS BIGGER DIAMETERS

FIGURE 5.36A EXAMPLES OF BANKERS AND STREAMCO WILLOW CUTTINGS

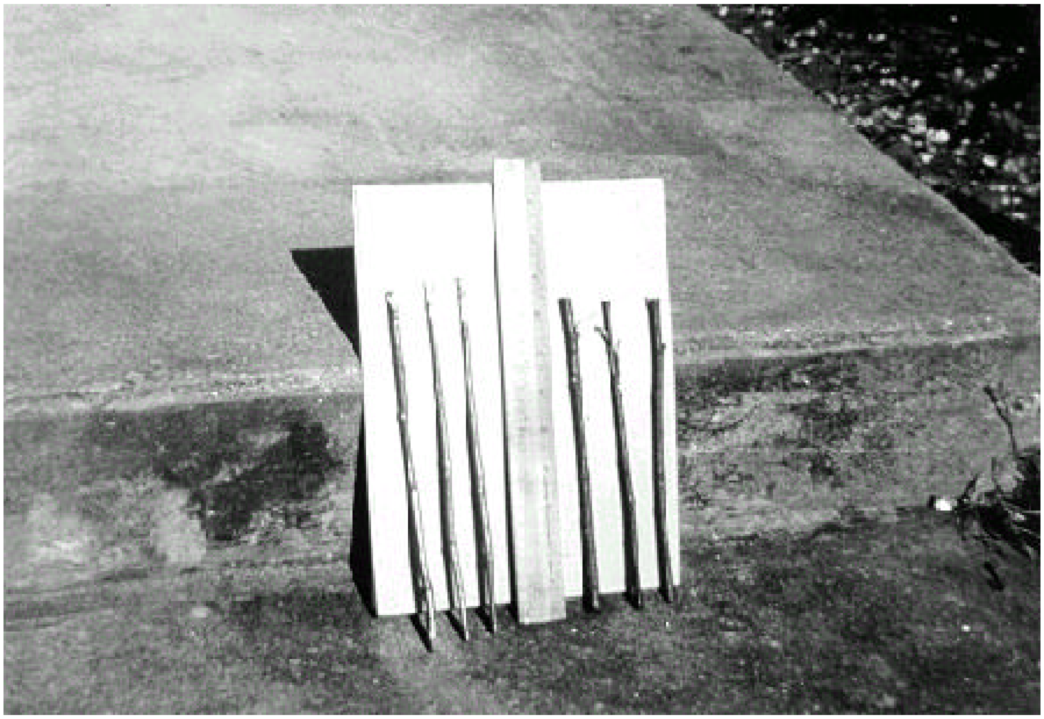


FIGURE 5.36B APPLICATION OF BANKERS AND STREAMCO WILLOW CUTTINGS

FIGURE 5.36C APPLICATION OF BANKERS AND STREAMCO WILLOW CUTTINGS

FIGURE 5.37 SEDGES AND GRASSES COMBINATION WITH BURLAP AND WOVEN FABRIC

FIGURE 5.38A WATTLING BUNDLE

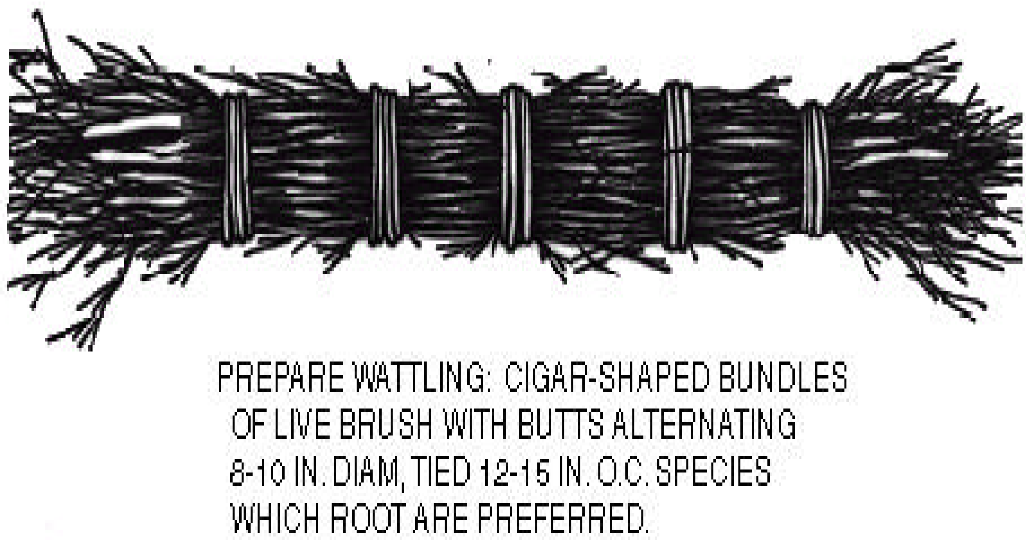


FIGURE 5.38B SCHEMATIC OF CONTOUR WATTLING

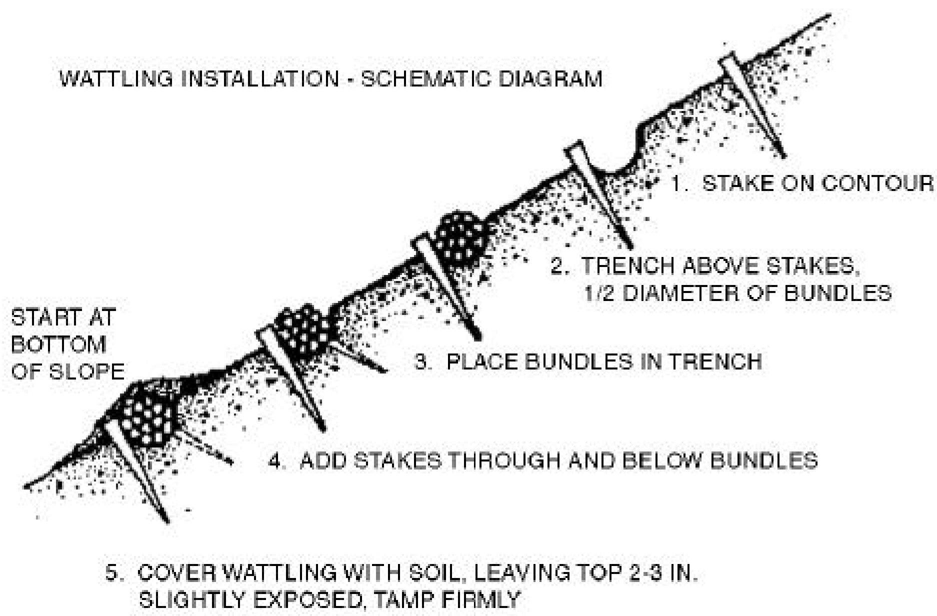


FIGURE 5.39 INSTALLING CONTOUR WATTLING

FIGURE 5.40 SCHEMATIC OF CONTOUR WATTLING SYSTEM

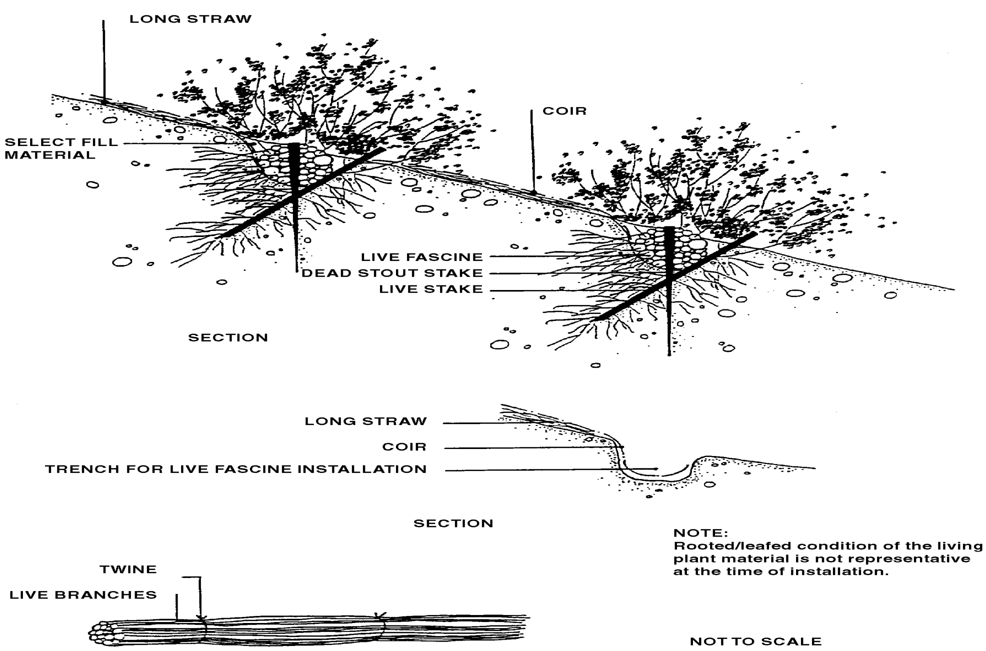


FIGURE 5.41 USE OF HYDROSEEDING AND HYDROMULCHING EQUIPMENT

6 PLANNING AND ALTERNATIVE SELECTION

The Planning Process

The planning phase leads logically to all actions in a project: setting goals and objectives, baseline data collection, design, construction and implementation, monitoring and evaluation, and maintenance and management. The only action that usually precedes the planning phase is the actual identification of the project itself. Projects are often driven by budgets, time limitations, environmental windows, resource needs, manpower, and stakeholders and partners.

Federal principles and standards recognize an established planning and policy protocol for environmental actions. However, this is a technical, non-policy handbook, and the Federal principles and standards are not always appropriate. Therefore, the planning process presented herein is directed towards bioengineering projects. This document is not meant as a replacement for agency specific guidelines and requirements. Several planning models have been proposed and most include the ten steps listed below. Small projects will not require the same level of attention and detail as larger, complex projects. However, this overall ten-step, common sense approach has been followed, adapted, and utilized in recent years by most experts in North America. The success of a streambank restoration project is nearly predetermined by Steps 1 and 2 below. Failure to involve the proper people and adequately define the project will lead to failures.

1. Form a Study Team

A well-organized interdisciplinary team must work together from the point of project inception to construction. Much has been written about team composition – usually listing numerous disciplines that should be involved. Agencies, individuals, and organizations with pertinent interests, including cost- and work-sharing partners and other stakeholders must be included. While it is recommended that the working team be kept small so that it can be cost effective, it is important to include all stakeholders at critical decision junctures.

2. Establish Project Objectives & Constraints

Forming objective and constraint statements can be the most challenging element of any water resources project. Objectives must be specific and achievable. Identify regional and site specific natural and physical resource needs. It is also recommended that physical constraints on the specific site and watershed be identified. Use a thorough thought-process that evaluates all possible approaches, that begins with a landscape or ecosystem overview and evaluation, and that sorts for ecological soundness, feasibility, cost-effectiveness, and practicality. The objectives and constraints are often driven not only by the physical impacts of erosion on the landscape, but by legal mandates, such as mitigation for some action on the stream.

3. Ascertain the System's Structural and Functional Relationships

In any ecosystem, there is a set of complex relationships between numerous dependent variables that dictate the physical, biological, chemical, and sociological character of the environment. Changes to any one variable, whether induced by nature or as a result of man's activities, cause the system to respond in ways that are not altogether predictable, and creates changes in many other variables. Restoration measures are attempts to manipulate the character of the ecosystem by modifying one or more system variables. Sometimes the manipulated variable is the target variable; more often, the management measure is applied to an easily managed variable in hope of secondary impacts to the target variable. Successful restoration requires a sound understanding of relationships between the state variables of the ecosystem.

4. Identify Alternatives for Achieving Project Objectives

Among the possible restoration approaches are a) returning a site to a condition that resembles its natural predisturbance state as closely as possible, b) modifying a site to replicate, as closely as practical, some target or "reference" system, and c) modifying a site to achieve specifically defined and quantifiable habitat objectives. All three cases entail modification of the target ecosystem's structure and function both locally and within its broader landscape or watershed context. The use of management measures is generally required to achieve the necessary ecosystem modifications. Management measures include a wide range of features and activities intended to change or cause a change in the ecosystem's structure or function. Once a decision to intervene directly has been taken, steps must be taken to ensure that solutions are matched to the problem(s) and can deal effectively with all of the ecological stresses, erosive processes, instability mechanisms and weakening factors responsible for the degradation of the project site.

5. Evaluate Alternatives and Select Management Measures

The general purpose of evaluating an aquatic ecosystem restoration or mitigation project is to help a decision maker identify and select appropriate management measures. Selected measures are generally those most likely to provide the greatest ecological benefits at the lowest cost, an especially important consideration in an era of budgetary constraints and enormous environmental challenges. In some cases, the "greatest" ecological benefit is not the objective, but rather a specific, quantified environmental or ecological benefit is sought. A conceptual design should be performed at this step. The analysis can be very brief but it should be sufficient to identify ball park quantities, costs and obtain a general confirmation of project benefits. The conceptual designs should also identify potential restrictions that would make a project non feasible. It is recommended that a schematic be produced with the concept design to facilitate communication, explain to the public meetings, define real estate needs, establish survey scopes, etc.

6. Detailed Design

After reaching a consensus on the schematic/conceptual site design, a detailed investigation is undertaken of the conditions on the restoration site. Appropriate plant materials are selected based on this site analysis and on evaluation of the plant communities in the nearby region. Specific site preparation needs are more clearly defined based on the detailed site analysis. Next a preliminary planting plan is developed consistent with project goals and objectives, site conditions and anticipated maintenance requirements. Guidelines are prepared for the subsequent design of an irrigation system (if needed) and specific measures for plant protection are identified. Methods and procedures for the installation of plant materials are outlined in the planting plan. Planning also needs to consider the maintenance of plant materials and the site during the plant establishment period and for any required or otherwise appropriate monitoring and reporting of project progress and success. The development of a preliminary cost analysis at this stage allows one to anticipate needs and re-evaluate approaches, if necessary, before everyone is committed to a specific implementation plan.

7. Review for Objective Accomplishment

Achieving all the stated goals for a restoration project is seldom possible. Though the alternative selection and design process should have allowed for refinement of the objectives, it is always a good idea to thoroughly review the design to assess the degree to which the objectives are likely to be met. This step is a form of a "sanity check" and helps uncover overlooked issues in the design process.

8. Develop Monitoring, Operation, and Maintenance Criteria

Monitoring is needed to a) assess project performance relative to the objectives, b) provide information needed to improve project performance, and c) disseminate results to interested parties. Monitoring requires that measurements be taken, based upon goals and objectives (and accompanying success criteria), to determine if the project is a success. Operation and maintenance follow naturally as actions predicated by the results of the monitoring effort.

9. Implementation

Many well-designed restoration projects are lost in the implementation stages. The need for QAQC is paramount. Good designs should account for construction practices, weather delays, and other contingencies - but unforeseen problems often arise and there is no substitute for on-site control and flexibility.

10. Monitoring and Follow-Up Actions

As discussed above, monitoring is critical to successful restoration projects. But the best monitoring plan is of little use if it does not stimulate suitable follow-up actions. Monitoring and follow-up are more critical for restoration projects than for conventional public works projects because the outcome is less certain and an adaptive management strategy must often be adopted.

Non-Restoration Alternative Considerations

While the focus of this document is on streambank restoration and stabilization techniques (emphasizing bioengineering), stream restoration and management entails a wide array of techniques and procedures ranging from removing stress factors through the implementation of BMPs to complete channel reconstruction. Generally speaking, these options perform best when used together as part of a comprehensive management plan.

A number of watershed and stream BMPs are presented in the following section. The remainder of the discussion will focus on the details of streambank restoration, though the tools and techniques presented are useful for a wide array of restoration and management options.

There are a number of control measures used to reduce the levels of pollutants in stormwater runoff from urban areas and construction sites. Some of these measures provide not only temporary control during construction, but can also serve as permanent features to mitigate impacts of development. Stormwater control practices can employ inexpensive techniques, such as settling, biological uptake of substances, and infiltration to treat stormwater. These techniques will remove some portion of most common pollutants and the practices presented here will apply to most situations. However, in situations involving very sensitive waters or unusual pollutants, it is possible that more sophisticated techniques will be required to meet NPDES discharge standards or other requirements. This section presents common stormwater control practices in use today. Each BMP includes a general description of the practice, lists a range of pollutant reduction for various pollutants, and presents some general design considerations, advantages and disadvantages.

STORMWATER PONDS

Since the 1970's, many local and state governments have attempted to mitigate the hydrologic affects of urbanization through the implementation of stormwater management practices primarily of the form of dry stormwater ponds. Dry detention basins, also called dry detention devices and ponds, temporarily detain a portion of stormwater runoff for a specified length of time, releasing the stormwater slowly to reduce flooding and remove a limited amount of pollutants. They are referred to as "dry detention" because these devices dry out between rain events. The original purpose of these ponds is to reduce the affects that development had on nuisance level flooding . The ponds were thus directed towards maintaining the post development peak discharge of the 2-year and sometimes the 10-year storm events. While stormwater ponds have met with success in controlling floodplain flooding and reducing the peaks of storm events, they do little to reduce the overall quantity of runoff. They can also have detrimental affects on stream stability over similar watershed conditions without the use of a pond since they maintain the flows that are considered to be dominant or erosive for longer duration's. In addition, pollutant removal in conventional dry ponds is low.

Many new ponds include a design feature called extended detention to address the deficiencies of conventional dry ponds. Extended detention ponds can provide both water quality benefits and reduce erosive flows. The most common design storms are 1-year rainfall event or the event that generates 0.5 inches of runoff. The first 0.5 inches of runoff is considered to provide a 'first flush' of the watershed and contains a significant concentration of pollutants. The one-year event is also considered to be a surrogate for dominant channel discharge. The design storms are detained for 12 to 24 hours as measured between the centroid of the inflow to the centroid of the outflow hydrograph . This results in a longer detention time and a decrease in the peak discharge over what would have occurred without the pond. The water quality benefits are provided by detaining water for enough time to allow sediments (and their attached pollutants) to settle to the bottom of the pond. The stream stability benefits are based on the premise that the increased volume of runoff from the developed watershed is offset by a reduced peak discharge. Many extended detention ponds include a permanent pool or wetland to enhance pollutant removal. These ponds are considered 'wet'. Typical stormwater basin removal efficiencies are listed below for selected pollutants.

Design Considerations. Design of stormwater ponds include locating proper sites for construction of the basin, calculating the appropriate detention time, dam safety concerns, design storm calculations, treatment of the expected range in volumes of stormwater from storms, and maintenance procedures and schedules. If safety concerns require a dry pond, the water table should be more than two feet below the bottom of the basin (to avoid a permanent pool of water in the basin during wet weather). Maintenance requirements should be considered due to the settling out of suspended sediments. To facilitate maintenance, a sediment forebay is recommended for these systems. A forebay is a section of the basin separated from the main part of the basin by a wall or dike and which receives the incoming stormwater. Forebays help capture debris and sand deposits, which accumulate quickly, and thereby ease routine cleaning. If stormwater ponds are designed without consideration to their relationship in the watershed, their interaction may result in an increase of peak discharge over what would have occurred if they had not been constructed at all. As a result, many stream restoration management plans involve the development of watershed hydrologic models so that the impacts of existing and proposed stormwater ponds on the watershed can be modeled.

Table 6.1 Stormwater Pond Pollutant Removal

Pollutant	*Conventional Dry Pond Estimated Removal Efficiency*	*Dry ED Pond Estimated Removal Efficiency*	*Wet ED Pond Estimated Removal Efficiency*
Plant Nutrients			
Total phosphorus ***Total nitrogen***			Moderate
Sediment			
Total suspended solids			High
Metals			
Lead ***Zinc***			Moderate to High Moderate
Organic Matter			
Biochemical and chemical oxygen demand (BOD or COD)			Moderate
Oil and Grease			Low
Bacteria			High
Stream Stability Enhancement	none	high	High
Maintenance Requirements	low	moderate	Moderate

Compiled from Schueler 1987; Schueler, et al. 1992; US EPA 1990; Phillips 1992; Birch, et al. 1992 and others.

Advantages. Dry detention basins are capable of removing significant amounts of pollutants and have proven effective at reducing peak storm flows. An appreciable body of knowledge has been accumulated on the design and maintenance of these structures. Detention basins can serve small to rather large developments and are usually readily incorporated into the design of the overall development. Retrofitting or modifying older storm water ponds to provide additional features such as extended detention can often provide significant benefits. Utilizing the existing storm water drainage system and area of the existing pond can be a cost effective approach to stream restoration in urban and suburban watersheds. However, it is important to note that adding additional control will involve changes in the stage-volume-discharge relationship of the existing pond. In addition, many of the existing ponds were built to satisfy local stormwater management laws; therefore, modifications may require maintaining the peak discharge control. To maintain the existing control as well as for dam safety concerns, additional volume and outlet structure modifications are often required.

Disadvantages. Dry basins can be unsightly, especially if floating and other debris accumulate in them. Dry basins are not very effective in removing pollutants from stormwater; therefore, the receiving water will have limited protection from pollution. Also, many pollutants that settle out are resuspended in the next storm flow and are discharged into the stream. Many dry basins end up with permanent pools of water because runoff from previous storms has not either flowed out or infiltrated before another storm occurs. The standing water can be a nuisance and an eyesore to residents.

Because they take up large areas, dry detention basins are generally not best suited for high-density residential developments. Sites must allow easy access for equipment to maintain and clean the basin and remove sediment. The appearance of some dry detention basins has been improved by planting hardy wildflowers in the bottom. Resident acceptance of a "wildflower basin" is much higher than of an unadorned open basin. The appearance of wet ponds can be improved by incorporating nature or fitness trails into their design. Many developments have utilized wet ponds as an asset to their community. The maintenance costs associated with extended detention basins are higher than dry basins. As with any shallow impoundment, a drawback for the use of wet pond is primarily thermal loading to downstream reaches. Affects of the structure on fish passage as well as public safety should also be considered.

Maintenance. Maintenance of dry detention basins is essential. Maintenance can be more extensive in wet ponds than in dry due to the settling out of suspended sediments. If they are not maintained, they can become a source of pollutants during dry weather. Other maintenance requirements include dam safety and the prevention of clogging. Normal maintenance costs can range from 3-5% of construction costs on an annual basis (Schueler 1987). Cleaning out sediment, which is expensive, will be necessary in 10 to 20 years' time. Cleaning involves digging out the accumulated sediment, mud, sand and debris with construction backhoe or other earth-moving equipment.

INFILTRATION (EXFILTRATION) DEVICES

Infiltration refers to the process of water entering into the soil, which indicates the predominant means by which these devices evacuate their treatment volume. There are a number of devices used to treat stormwater that make use of infiltration to remove pollutants and to recharge or replenish the ground water. Infiltration devices include infiltration basins, infiltration trenches and dry wells. The term exfiltration is also frequently used in reference to these BMPs, coming from the perspective of the device rather than its setting. Properly designed infiltration devices can closely reproduce the water balance that existed pre-development, providing ground water recharge, control of peak flows from stormwater and protection of streambanks from erosion due to high flows. They provide quasi-habitat benefits through increased baseflow and water quality benefits though filtration. A significant advantage of infiltration is that in areas with a high percentage of impervious surface, infiltration is one of the few means to provide significant groundwater recharge.

Infiltration devices can remove pollutants very effectively through adsorption onto soil particles, and biological and chemical conversion in the soil. Infiltration basins with long detention times and grass bottoms enhance pollutant removal by allowing more time for settling and because the vegetation increases settling and adsorption of sediment and adsorbed pollutants. Although infiltration is a simple concept, infiltration devices must be carefully designed and maintained if they are to work properly. Poorly installed or improperly located devices fail easily. It is critical that infiltration devices only be used where the soil is porous and can absorb the required quality of stormwater. Maintenance needs for infiltration devices are higher than other devices partly because of the need for frequent inspection. Nuisance problems can occur, especially with insect breeding, odors and soggy ground.

Pollutant removal capability for infiltration basins that exfiltrate the entire amount of captured stormwater is shown below. Other infiltration devices which exfiltrate only part of the captured stormwater (some of the stormwater is discharged to receiving waters on the surface) have lower removal effectiveness.

Table 6.2 Infiltration Devices Pollutant Removal

Pollutant	*Estimated Removal Efficiency*
Plant Nutrients	
Total phosphorus	high
Total nitrogen	high
Sediment	
Total suspended solids	Very High
Metals	
Trace metals (sediment-bound)	Very high
Organic Matter	
Biochemical and chemical oxygen demand (BOD)	Very High
Oil and Grease	High
Bacteria	Very High
Stream Stability Enhancement	low
Maintenance requirements	high

Compiled from Schueler 1987; Schueler, et al. 1992; US EPA 1990; Phillips 1992; Birch, et al. 1992 and others

Design Considerations. Some infiltration devices (infiltration trenches, dry wells, and catch basins) can be constructed under parking lots and roads, taking very little land from other uses. Other infiltration devices take up considerable areas, depending on their size and the drainage area served. Locating smaller infiltration devices is fairly easy so that large downstream devices can be replaced with a number of small structures upstream and still achieve the same control of stormwater. The effectiveness of infiltration devices is dependent on well drained soils. Infiltration devices require permeable soils and reasonably deep water tables. Smaller infiltration devices such as dry wells basins can be located near buildings to capture the runoff from roofs and other impervious surfaces.

Advantages. Infiltration devices help replenish the ground water and reduce both stormwater peak flows and volume. Pollutant removal can be very high for many pollutants. Because they take up little land area and are not highly visible, many underground infiltration devices can be located close to residential and commercial areas.

Disadvantages. Infiltration techniques work only where the soils are permeable enough that the water can exit the storage basin and enter the soil. These devices have a limited design life and a very high failure rate where soils are not extremely well drained. Infiltration devices must have sediment removed before the stormwater enters the device to prevent clogging of the soil. The water table must be at least two feet under the bottom of the device. Infiltration devices do not typically provide any effective peak reduction or stormwater reduction.

Maintenance. Maintenance requirements include regular inspections, cleaning of inlets, mowing and possible use of observation wells to maintain proper operation. A sediment forebay is recommended since many of the infiltration designs that are currently in use are prone to failure by clogging. Infiltration basins and sediment removal devices used to prevent clogging of other infiltration devices must have the sediment removed regularly. If an infiltration device becomes clogged, it may need to be completely rebuilt.

OIL AND GREASE TRAP DEVICES

A number of devices are used to remove oil and grease from stormwater. One type, commonly known as oil-water separators, are mechanical devices manufactured by various industrial equipment manufacturers and usually installed at industrial sites. These devices employ various mechanisms, some of which are proprietary, to separate oil from stormwater, which is then discharged to a treatment plant or to a receiving water. Oil-water separators usually require support from the manufacturer and are best used where these devices can be properly maintained and frequently inspected, such as at industrial sites. Information concerning these devices, their installation, use and requirements can be obtained from the manufacturer or a consultant. Another type of oil and grease removal device is the oil and grease trap catch basin (or oil and grit separator). These catch basins are underground devices used to remove oils, grease, other floating substances and sediment from stormwater before the pollutants enter the storm sewer system. They are usually placed to catch the oil and fuel that leak from automobiles and trucks in parking lots, service stations, and loading areas. A third type of device is a simple skimmer and control structure used at the outlet of a sediment basin (forebay), typically used prior to discharge into a larger detention device. This section discusses the latter two designs.

A popular design for the oil and grease trap catch basin uses three chambers to pool the stormwater, allow the particulates to settle and remove the oil. As the water flows through the three chambers, oils and grease separate either to the surface or sediments and are skimmed off and held in the catch basin. The stormwater then passes on to the storm sewer or into another stormwater pollution control device. Because these devices are relatively small and inexpensive, they can be placed throughout a drainage system to capture coarse sediments, floating wastes, and accidental or illegal spills of hazardous wastes. Oil and grease trap catch basins can reduce maintenance of infiltration systems, detention basins and other stormwater devices. Since these catch basins detain stormwater for only short periods, they do not remove other pollutants as effectively as facilities that retain runoff for longer periods. However, these basins can be effectively used as a first stage of treatment to remove oil and sediment from stormwater before it enters another, larger stormwater pollution control device, such as a wet pond. The second design involves an open sedimentation basin with a skimmer plate extending below the ponding control elevation at the outlet. Stormwater velocities are reduced in this sump, dropping out coarse sediment and separating oils and greases and floatables, which are retained in the basin by the skimmer as the stormwater discharges to a larger detention device or off-site. These sediment sump/skimmers are often designed larger than the underground chambers, have longer detention times, and thus remove more of the sediments and oils and greases.

Pollutant removal varies depending on the basin volume, flow velocity, and the depth of baffles and elbows in the chamber design. Well maintained catch basins should remove the following levels of pollutants, with the open sump/skimmer design showing somewhat higher levels.

Design Considerations. Oil and grease trap catch basins can be installed in most areas. Drainage areas flowing into the catch basin must be no larger than two acres and the catch basin must be large enough to handle dry weather flows that enter the basin. They are often used for rooftops and parking garages. These catch basins can be installed in almost any soil or terrain, which allows their use near or at the impervious surfaces contributing heavily to the stormwater runoff. Little land area is taken up by catch basins as they require only enough area for proper maintenance. Oil and grease skimmer design is essentially that of a sedimentation basin with a control structure discharge that allows for mounting of a skimmer plate. The plate should extend sufficiently below the lowest discharge level to preclude siphoning of the water surface by the discharge.

Table 6.3 Oil and Grease Trap Pollutant Removal

Pollutant	*Estimated Removal Efficiency*
Plant Nutrients	None
Sediment	
Total suspended solids	Low
Metals	
Trace metals	Low
Oil and Grease	High
Organic Matter	Low
Bacteria	Low
Stream stability enhancement	none
Maintenance requirements	very high

Compiled from Schueler 1987; Schueler, et al. 1992; Phillips 1992; Birch, and Pressley. 1992.

Advantages. Oil and grease trap catch basins are easily installed in most areas. Since these devices are underground, there should be few complaints concerning appearances. These catch basins can be used very effectively as part of a system of stormwater controls to remove oily pollutants and coarse sediment before they enter another stormwater control device. Also small catch basins can be distributed over a large drainage area, which may prove advantageous over constructing a single large structure downstream. Sediment basins with skimmers are simpler and more easily maintained than the chamber design, tend to be larger and more effective in their role, and allow for photodegradation of hydrocarbons in addition to settling.

Disadvantages. Pollutant removal is low for contaminants other than oil, grease and coarse sediment for both types of systems. Both must have the accumulated sediment removed or cleaned out frequently to prevent sediment-bound pollutants from being stirred up and washed out in subsequent storms. Sediment removal removes the oil and grease because these pollutants eventually bind to the sediment. The chamber type is more difficult to maintain because of its enclosed, underground design, and typically is less efficient than the sediment basin because it tends to be smaller. Odors are sometimes a problem. These devices do not contain a significant enough volume to provide any effective peak reduction or stormwater reduction.

Maintenance. These devices are maintenance intensive and require a long term commitment. Oil and grease trap catch basins require regular inspection and cleaning at least twice a year to remove sediment, accumulated oils and grease, floatables, and other pollutants. Sump/skimmers require periodic but less frequent sediment removal. They should be inspected on a frequent basis. If material is allowed to build up in them, they easily become a pollutant source during dry weather and can be more of an environmental detriment that if they had not been constructed. Wastes removed from these systems should be tested to determine proper disposal methods. The wastes may be hazardous; therefore, maintenance costs should be budgeted to include disposal at a proper site. These disposal costs can be significant.

SAND FILTERS

Sand filters are a type of stormwater control device used to treat stormwater runoff from large buildings, access roads and parking lots. As the name implies, sand filters work by filtering stormwater through beds of sand. Small sand filters are installed underground in trenches or pre-cast concrete boxes. Large sand filters are above-ground, self-contained sand beds that can treat stormwater from drainage areas as much as five acres in size.

To date, the city of Austin, Texas and the state of Florida have made use of the large, above-ground versions of sand filters, while the underground sand filters have been installed in Florida, Maryland, Delaware and the District of Columbia. Both above-ground and underground versions use some form of pre-treatment to remove sediment, floating debris, and oil and grease to protect the filter. After the stormwater passes through the pre-treatment device, it flows onto a sand filter bed. As the stormwater flows through the filter bed, sediment particles and pollutants adsorbed to the sediment particles are captured in the upper few inches of sand.

The underground versions fit in very well in urban areas and on sites with restricted space. Depending on the design, the underground sand filters are practically invisible to casual observers and generally receive few complaints from residents. Maintenance of these sand filters is simple and done manually. Above-ground sand filters are often considered to be eyesores by residents. Thus, these sand filters are best used where they cannot be seen or where hedges or other visual barriers can be installed. Because of the construction techniques used to build above-ground sand filters, large filters are proportionately less expensive than small filters. Construction costs can be kept lower if lightweight equipment is used for maintenance, which reduces the structural reinforcing needed in the filter.

Pollutant removal for sand filters varies depending on the site and climate. Overall removal for sediment and trace metals is better than removal of more soluble pollutants because the filter functions by simply straining small particles out of the stormwater. Table 6.4 lists removal rates.

Table 6.4 Sand Filter Pollutant Removal

Pollutant	*Estimated Removal Efficiency*
Plant Nutrients	
Total phosphorus	Moderate
Total nitrogen	Moderate
Sediment	Very High
Metals	
Trace metals (sediment-bound)	Very High
Organic Matter	
Biochemical oxygen demand (BOD)	Moderate
Oil and Grease	High
Bacteria	Moderate
Stream Stability Enhancement	none
Maintenance	moderate

From Schueler, et al. 1992.

Design Considerations. Sand filters remove pollutants by settling out particles in the pretreatment devices and by straining out particles in the filter. Underground sand filters built in two-chambered precast concrete boxes cannot handle large drainage areas. Moderate to large parking lots should be the largest areas drained to underground sand filters. Sand filters constructed underground should have pretreatment or settling chambers that hold 540 cubic feet of water for each acre of drainage area contributing stormwater to the sand filter (Shaver 1992). For two-chambered sand filters, the volume of the filter chamber should equal the volume of the settling chamber and the sand filter bed should be 18 inches deep (Shaver 1992). The surface area of both the settling and filter chambers should have 360 square feet of area for each acre of drainage area (Shaver 1992). Above-ground sand filters, built on the land surface, can handle drainage areas up to five acres in size. The sand filter bed should be 18 inches deep. Above-ground sand filters may use grassed filter strips, grassed swales or large basins to pretreat the incoming stormwater to prevent clogging of the sand filter.

Advantages. Sand filters can be installed underground in urban settings and be kept out of sight, or above ground for large drainage areas. Sand filters can provide effective reduction of the more common urban pollutants in stormwater. Sand filters have demonstrated long lifetimes and consistent pollutant removal when properly maintained. Maintenance for sand filters is simple and inexpensive. Mosquito breeding is usually not a problem, even in underground settling chambers that hold pools of water for long periods. Shaver (1992) reports that oil and grease in the stormwater form a sheen on the water, which prevents mosquito growth.

Disadvantages. Sand filters are more expensive to construct than infiltration trenches. If heavy equipment is to be used for maintenance, construction costs are significantly higher. Sand filters on the land surface are considered unattractive. Sand filters provide no stormwater detention and provide only limited removal for a number of pollutants.

Maintenance. Sand filters require frequent but simple maintenance. Maintenance for smaller, underground filters is usually and best done manually. Normal maintenance requirements include raking of the sand surface and disposal of accumulated trash. The upper few inches of dirty sand must be removed and replaced with clean sand when the filter clogs. The pretreatment devices must be cleaned to remove sediment and debris. If the pollutant load of the stormwater is high, the entire sand filter may need to be periodically replaced.

OTHER BEST MANAGEMENT PRACTICES (BMPs)

Following is a list of various BMPs that have proven useful in restoring and maintaining watersheds and stream systems. In many locations, one or more of these BMPs are required by statute, or may be imposed as a permit condition.

- Where possible, conserve existing riparian vegetation.
- Avoid construction activities to the extent possible during the rainy season.
- Where possible, drain roof tops and paved areas into underground dispersal pipes or vegetated infiltration beds.
- Keep concentrated development away from sensitive areas such as riparian areas and wetlands.
- Roadways and drainage ditches should be managed and maintained to avoid sediment production and movement.
- Revegetate, mulch, or otherwise protect disturbed areas at all construction sites as soon as possible after disturbance.
- Establish temporary berms to contain waste water and irrigation installation overflows onsite in construction areas.

- Increase the use of permeable surface to encourage infiltration of rainfall into the soil, and decrease peak storm runoff.
- Transport channeled water safely across roadway.
- Undertake Dry Season Maintenance a program that includes:

  Repair energy dissipaters
  Clean culverts
  Replace inadequate culverts
  Smooth out rills to prevent them from forming into gullies.
  Modify surface drainage as needed.
  Seed exposed soil.

- Undertake Wet Season Maintenance a program that includes:

  Inspect energy dissipaters
  Keep culverts and ditches clean.
  Check rill erosion and construction of waterbars. Note any changes in surface or cross drainage.

- Minimize New Road Construction
- Remove and revegetate abandoned roads.
- Design trails with waterbars and other erosion prevention techniques such as eliminating "crossover" access on switchback trails.
- Maintain erosion control practices during fall activity.
- Control vehicle access to limit vehicles in unpaved areas.
- Provide sediment control, mulching and reseeding for areas cleared by heavy foot traffic, such as picnic areas or meeting areas.
- Carefully design trails to minimize damage from mountain bikes and horse traffic, etc. Provide a wide range of publicly accessible recreational experiences and environments, to minimize pressure on unmanaged areas.
- Encourage golf courses, parks and public recreation areas to protect streams flowing through the properties by shielding them from direct access exception areas designed for access. Include erosion and sediment control as a priority when planning soil-disturbing activities and projects in the watershed.
- Encourage infiltration beds between driveways or parking lots and road ditches.

Streambank Restoration and Stabilization

Tables 6.5, 6.6 and 6.7 present a decision support matrix to aid in the selection of structural solutions for streambank restoration. This can only be a guide, because in practice each problem has individual elements that cannot be generalized, and every design is to some degree unique. At present there are no 'cook book' solutions to bank retreat problems and guiding principles must be applied in a flexible design strategy that ensures protection is adequate, cost-effective, safe, and environmentally acceptable.

Effectiveness

Inherent factors in the properties of a given bank stabilization technique, and in the physical characteristics of a proposed work site, influence the suitability of that technique for that site. In this context, it is important to distinguish suitability, which is governed by those inherent factors, from adequacy, which is governed by design decisions. In other words, the selection phase focuses on suitability, while the design phase focuses on adequacy. Both of these then determine the effectiveness of the work. Many techniques can be designed to adequately solve a specific bank stability problem, to resist erosive forces and geotechnical failure, although there are certainly exceptions, which will become apparent in later discussion. The challenge to an engineer is to determine the most suitable, the most effective solutions to a specific problem, to recognize the techniques that match strength against strength, that perform most efficiently when tested by the strongest mechanism of failure.

Table 6.5 Selection of Appropriate Structural Solutions for Erosion Processes

Failure Type	*Structural Considerations*	*Options for Structural Protection*
Parallel flow (fluvial entrainment)	Structures may either increase erosion resistance by armoring the bank with a non-erodible layer or reduce the intensity of attack by deflecting currents away from the bank. Flow attack is usually concentrated on the lower half of the bank	Revetments are used to provide surface armoring. Deflectors may be formed by dikes or groins. Soft systems use vegetation, hybrid systems use geogrids, geotextiles and cellular blocks with vegetation. Heavy protection uses riprap, armorstone and gabions at the toe, often with lighter protection on the upper bank.
Impinging flow (fluvial entrainment)	Impinging flow generates very high turbulence, secondary currents and elevated local velocities. Instantaneous shear stresses and near bank scour depths are large, but unpredictable.	Uncertainties associated with the intensity of attack by impinging prescribe the use of heavy protection. Use of soft or hybrid protection is inadvisable unless the channel is realigned to eliminate flow impingement. Realignment will have other benefits.
Boatwash	Chronic or severe boatwash erosion may persist at vulnerable places even in well-managed waterways These locations may require structural protection.	Hard protection using a vertical wall protects the bank but may reflect wave energy against unprotected banks. Porous revetments and emergent vegetation are excellent energy dissipators. In most cases there is scope for use of wet berms and soft engineering.
Wind-waves	Wind-waves have a wider wavelength than boat waves but are rarely a spectrum of heights and serious problem on British inland waterways.	Structural protection should be designed to absorb and dissipate wave energy without significant erosion and without reflecting it. A wet berm with emergent vegetation is recommended.
Rills and gullies (surface erosion)	Rills and gullies pose threats to the integrity of the bank surface including any surface protection.	Surface drainage may be controlled to prevent erosion using buffers, pipes, drop structures and lined channels.
Piping (seepage erosion)	Piping erosion is a common cause of failure of structural bank protection. A notch produced by piping is easily misinterpreted as due to boatwash.	A structural solution must allow free subsurface drainage while preventing loss of soil particles. This is best achieved by use of a granular, geotextile or vegetative filter.

Matching the solution to the problem

This may require a simple survey of the river reach or professional advice. Once the cause has been determined, you can then design and carry out revegetation works with confidence - matching the type and position of vegetation to the nature of the problem and combining it, if necessary, with structural work.

Table 6.6 Selection of Appropriate Structural Solutions for Failure Mechanisms

Failure Type:	*Structural Considerations*	*Options For Structural Protection*
Shallow slide	Shallow slides occur because the bank angle exceeds the angle of repose. Surface armor installed to prevent erosion.	The best solution is to regrade the bank to an angle lower than the slides can disrupt angle of repose and protect the toe from further erosion. If space is limited a vertical wall can be used but deep toe scour will occur.
Rotational slip	This type of deep-seated failure threatens protection structures and surface treatments. It is not amenable to shallow solutions.	Major regrading coupled with toe protection and improved drainage will be necessary to achieve geotechnical stability. If limited space precludes regrading, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures
Slab-type failure	Slab-failure planes pass below the rooting layer and shallow stabilization measures or positive pore pressures may be critical.	Regrading to a lower bank angle will eliminate tension cracks. Tension cracks protection is installed to prevent further over-steepening. If limited space precludes this, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures.
Cantilever failure	Cantilevers are produced by erosion of a weak layer in the bank.	Measures that may be applied include armoring of the bank to prevent undermining of the weak layer, installation of a filter to prevent piping, and re-vegetation to increase soil tensile strength.
Soil fall	Soil fall occurs on steep, undercut banks of low cohesion. It adds to bank retreat due to flow, wave or piping erosion.	Soil fall may be eliminated by regrading the bank to a lower angle and protecting the surface with vegetation, a geotextile or a riprap. If lack of space precludes this, the steep bank may be stabilized by a vertical wall with suitable allowance for deep toe scour.
Dry granular flow	Dry granular flow is a surface failure that occurs on undercut banks, which have no effective cohesion.	Dry granular flow is dealt with by soil reinforcement using a geogrid, geotextile or vegetation coupled with toe protection to prevent further undercutting and active management to prevent trampling or mechanical damage to the upper bank.
Wet earth flow	Wet earth flow and liquefaction may pose a threat to bank protection and structural stabilization schemes.	Improvement of subsurface drainage is the key to prevention of wet earth flows. Steps involved include installation of pipes or drains to remove water and filters to retain soil particles.

Suitability to site conditions

Selected techniques must be suited to the site conditions. In later sections, more information will be presented on the site requirements for various treatments. Often, more than one technique is suitable to the site conditions and a ranking of alternatives is useful. This notion is shown in Table 6.8, which presents guidelines for a few techniques when the site conditions are defined in terms of the nature of the erosion or bank failure problem.

Table 6.7 Selection of Appropriate Structural Solutions for Weakening Factors

Weakening Factor:	*Structural Considerations*	*Options for Structural Protection*
Leaching	Leaching is difficult to detect and may seriously weaken the soil thereby threatening the integrity of the bank.	The structural solution is to strengthen the soil artificially by injecting grout or resin into the bank, but this will rarely be cost-effective.
Trampling	Trampling weakens the bank by destroying the soil fabric and it can also increase surface runoff.	Conventional structural treatments include concrete and bitumen to create footpaths and animal ramps. Modern alternatives use geogrids and cellular blocks that protect the surface while allowing vegetation to grow through them, producing a natural appearance.
Destruction of riparian vegetation	The structural role of vegetation in bank geotechnics is poorly understood but is often crucial to stability.	The best structural protection to prevent destruction of riparian vegetation is a fence. The creation of a fenced riparian buffer zone is highly beneficial when stabilizing, protecting and conserving a streambank. Destruction of bank vegetation can also be prevented structurally by using buttresses to stabilize the roots of undercut trees and geogrids and cellular blocks to promote riparian vegetation, and pocket fabrics for aquatic and emergent plants.
Mechanical damage	Mechanical damage may compromise the structural strength of the bank directly, or it may destabilize the bank indirectly by providing a foothold for a necessary range of erosion processes and weakening factors.	The form of a structural solution depends on the activities responsible for mechanical damage. Heavy protection will be where activities such as boat mooring or angling impose intense stresses. Where activity is less severe, hybrid and soft protection may suffice.
Positive pore water	High pore water pressures may be disastrous to bank stability and are often responsible for the failure of bank stabilization schemes.	Structural solutions must dissipate pore pressures by allowing water pressures to drain through the bank while retaining soil particles. The detailed design is a topic in geotechnical engineering, but a variety of perforated pipes and filters are used to eliminate excess pressures.
Desiccation	Cracking and crumbling due to desiccation can lead to significant reduction in the operational strength of bank soils.	Structural solution through the installation of a light reinforcement system based on a geogrid, geotextile or suitable vegetation is an appropriate approach that retains a natural appearance to the bank.
Freeze/thaw (frost erosion)	In Britain erosion caused by freeze/thaw erosion alone does not merit a structural solution.	The intensity of freeze/thaw processes in Britain does not pose a hazard to soft or hard bank protection, which will be able to withstand the forces exerted without special design features.

Table 6.8 Selected Erosion Protection Measures for Streambanks

Erosion Problem	*Streambank Protection Measures Ranked by Environmental Benefits*
General bank scour	1. Brushmattress
	2. Live fascine
	3. Live staking
	4. Joint planting
	Stone toe?
Toe erosion and upper bank failure	1. Live cribwall
	2. Brushmattress with rock toe
	3. Joint planting
	stone toe?
Local streambank scour	1. Branchpacking
	2. Live cribwall
	3. Live fascine with erosion control fabric
	4. Joint planting
	stone toe?
	rootwads?
Overbank runoff. Intercept and divert runoff and repair damage with:	1. Branchpacking
	2. Live fascine
	3. Live staking with erosion control fabric

Adapted from Robbin B. Sotir and Associates

Durability

Durability is affected by a number of factors including: required project life; maintenance requirements and capability; climatic conditions; debris loads, including ice; corrosion and abrasion; susceptibility to vandalism, animals, insects, and fire

To reduce problems with vandalism and theft, select a technique that minimizes temptation. Some materials that are obvious targets for vandals and thieves are posts, boards, concrete blocks and stones of attractive size and shape, small cables and wire, and easily removable fasteners. Animals can occasionally be a problem to consider in the evaluation of the durability of a stabilization method. Beavers, cattle, deer, rabbits, and other animals may find tender young vegetation on new stabilization plantings to their liking. Protective measures may be required, thus increasing the cost.

Experience has shown a number of other practices to improve durability and success. Use temporary protection by fencing, netting, or wrapping until vegetation becomes well established. Reduce temptation by using less palatable species of vegetation. Use species that vigorously resprout. Insect damage can be a problem for wooden components or vegetation. Preservative treatment for wooden components is common practice, and chemical treatment of vegetation at vulnerable stages may be feasible. Environmental considerations may rule out these options for some projects.

Safety

Selection of a safe technique is a site-specific endeavor. Each alternative should be weighed in light of potential uses of the project site to identify possible safety concerns. Obvious examples include potential danger to recreational boaters from some types of indirect protection, or the possibility of people toppling off an unguarded retaining wall. In urban or recreational areas especially, seeking the advice of a safety specialist, and perhaps even legal advice, is well-advised.

Cost

Cost considerations are usually addressed in the alternative selection process by using a matrix approach to eliminate cost-prohibitive methods from further consideration, followed by more precise estimates in the final design stage. For small projects, costs can be closely estimated and are based principally on construction labor and materials. Additional expenses include equipment and tools (Table 6.9).

Table 6.9. Suggested Hand Tools Typical Costs

Item	*Cost*
Axe - regular size	$17.75
Chain saw chains	$25.00
Chain saw pants	$50.00
Dead blow hammers - 4 lbs.	$25.00
Eye protection goggles	$10.95
Files - chain saw	$3.95
Files - loppers	$9.95
Files - shovels & hand clippers	$5.25
Hammers - regular	$5.00
Hand pruning shears	$8.75
Leather work gloves	$9.95
L.oppers	$24.90
Mattock - Pick & hoe	$21.50
Measuring tapes - 100 feet	$20.95
Round point shovels	$23.95
Shovel handles	$8.60
Sledge hammer - Regular size 8 lbs.	$33.70
Sledge hammer handle - 8 lbs.	$14.95
Sledge hammer hand size 2 lbs.	$18.00
Sledge hammer handles - 2 lbs.	$8.60
Wire cutters	$7.95

In the plan of development, consideration should be given to the equipment and materials required for vegetation handling and planting at the implementation stage. The tools required and the planting techniques will depend on the type of vegetation, i.e., woody or herbaceous, the size of plants, soils, and the size of the project and site conditions. Freshwater herbaceous plantings with low wave or current energy environments may call for tools like spades, shovels, and buckets. In contrast, high energy environments of waves and currents may require tools for bioengineering installations. Such tools include chain saws, lopping and hand pruners for the preparation of woody cuttings, and materials for woody bioengineering methods; or heavy hammers and sledges for driving stakes in bioengineering treatments such as wattling and brush matting. Specialized equipment may be required. This is true when moving sod or mulches containing wetland plants or plant propagules. It is also true since bioengineering projects often have the constraints of working in a pristine stream system where riparian corridors are extremely valuable, particularly in large, urban settings. It is in these settings that equipment size and type constraints are often placed upon the project. Thus, downsized front-end loaders and walking excavators are sometimes required to minimize disturbance of existing vegetation and soil. Other equipment and materials may include fertilizers, soil amendments, (i.e. lime), fencing for plant protection, and irrigation equipment for keeping plants alive during dry conditions. Other equipment and materials for keeping plants alive before they are planted may include shading materials such as tarps, buckets with water for holding plants, and water pumps and hoses for watering or water trucks.

For larger projects, the final estimate should consider incidental items such as rights-of-way (ROW), engineering and design (E&D), supervision and inspection of construction (S&I), operation and maintenance (O&M), and contingencies. These items may simply be estimated as a percentage of construction cost, or a more precise estimate may be appropriate. In the selection phase, it matters only if there are substantial differences in these factors among the methods being considered, which is not usually the case. The exceptions are:

- Differences in ROW cost would occur if one method could be constructed with floating plant, but another method would require extensive ROW on the bank in a developed area.

- Significant difference in E&D cost may exist if methods are being considered for which standard specifications exist, or for which design assistance is available from the manufacturer or supplier, if your procurement policies permit specifying a particular product "or equal". These would require less E&D effort than methods for which original specifications must be developed. Also, the data required for analysis and design, may vary from method to method. For example, precise riprap design requires hydrologic and hydraulic analysis, and precise geotechnical design requires expensive field and analytical work. Methods requiring pile-driving may need borings to document sub-surface conditions.

- Methods requiring longer to construct, such as labor intensive methods, or intensive inspection, such as underwater placement of stone, would have a higher S&I cost than quickly constructed techniques.

In practice, O&M expense for well-designed work is low, and quantitative comparison of different methods is difficult unless a method is being considered which obviously requires expensive monitoring and future maintenance and reinforcement. A sophisticated analysis requires a comparison of "life-cycle" costs, the procedure for which will usually be specified by institutional policy.

Contingencies are routinely expressed as a percentage of the estimated cost, but again, if unpredictable changes in site conditions or materials or fuel costs would impact some methods more than others, good practice would be to weight the estimate of contingencies.

Capital vs. Project Cost

Bioengineering treatments are normally much less expensive than traditional methods of streambank erosion control, e.g., riprap revetment, bulkheads, but not always depending on the environmental setting and the project objectives. Costs can vary tremendously by availability of materials, hauling distances, prevailing labor rates for the geographic area, and a host of other factors.

When comparing bioengineering methods with traditional engineering applications, each must be considered on its merits, comparing life-cycle costs, i.e. the net present value of investigation, design and construction, plus future management and replacement. As mentioned earlier, bioengineering will require a higher investment early in the project life to ensure that the living system is established.

Then, maintenance drops off and the vegetation in the bioengineering treatment continues to grow, spread, and strengthen the streambank. Some maintenance costs may be associated with the bioengineering treatment later in the project life, but these costs will be rather small. In contrast, the traditional treatment using inert structures, such as riprap revetment, will have a high construction cost and a substantial replacement or refurbishment cost.

Costs are also difficult to compare when strictly looking at currency per unit of measure. The most common denominator for arriving at costs seems to be labor in terms of person hours it takes to build and install the particular treatment. Then, material costs and equipment rental, etc., would have to be added onto this. The authors could not document time for all of the bioengineering methods mentioned in the text, but some man-power estimates are given in the following paragraphs. Also, manpower costs are given for general applications of seeding and vegetative plantings to supplement the bioengineering treatments.

Man-hour Costs of Bioengineering Treatments

Table 6.10 gives labor estimates for various kinds of vegetative and bioengineering treatments depending on available information. Please note that these vary quite a lot and depend largely on nearness to site, prevailing labor rates, etc.

Table 6.10 Vegetative and bioengineering labor estimates.

ACTIVITY	***LABOR REQUIRED***
Wattling	2-5 m/hr
Brush Layering	2-5 m/hr
Brush Mattress	0.2 - 1.0 m^2/hr
Dormant Posts	10 - 20 posts/hr
Willow Cuttings	45 - 50 cuttings/hr
Plant Roll	6 m/hr
Coir Fascine	1.5 m/hr
Sprig Planting	4.0 – 20 m^2/hr
Seedling Planting	30 – 120 plants/hr
Ball & Burlap Shrubs	10 - 25 plants/hr
Containerized Plants	20 - 40 plants/hr
Vegetative Geogrids	0.2 - 0.4 m/hr
Seeding	0.02 – 0.2 ha/hr
Hydroseeding	0.05 – 0.15 ha/hr

Following is a discussion of costs in terms of structures. Once again, costs can vary considerably. Costs of structures will depend primarily on:

1) Cost of materials, e.g., cost of quarry run rock,
2) Cost of transportation to the site, e.g., haul distance of rock, and
3) Placement or installation costs, e.g., transferring rock to a barge and placement at site off a barge.

Brush Mattress or Matting

The cost of the brush mattress is moderate according to Schiechtl (1980), requiring 2 to 5 man-hours per square meter. In a training session that WES conducted, a crew of 20 students using hand tools installed about 18 sq. m of brush mattress at a rate of about 1 man-hour per square meter. This rate included harvesting the brush, cutting branches into appropriate lengths, and constructing the mattress. This rate of production compares favorably to an average rate of .92 sq. m of brush mattress per man-hour by a leading bioengineering firm in the United States.

Brush Layering

There are few references on the cost of brush layering. Schiechtl (1980) reported the cost to be low, presumably in comparison to techniques using riprap or other similar materials. In the training session mentioned earlier, a crew of 20 students using hand tools installed about 20 m of brush layering along one contour-slope in about 30 min. This equates to 2 m per man-hour. Often, costs can be reduced if machinery such as bulldozers or graders can gain access to the shoreline site and reduce the hand labor required in digging the trenches. Then, this would only require workers to fill the trenches with brush, which can also be covered with machinery.

Wattling Bundles (Fascines) and Cuttings

Leiser (1983) reported man-hour costs for installing wattling and willow cuttings at Lake Tahoe, California. These man-hour costs can be extrapolated to streambanks as well and run about 6 lineal ft of wattling per man-hour and 46 small willow cuttings per man-hour. Robin Sotir quoted an average installation rate of 5 lineal ft of fascine production per man-hour. Obviously, if one were to place a coir fabric between contours of wattling bundles, production rates would decrease substantially. According to Ms Sotir, who has done this extensively, it would probably half the amount of linear ft per man-hour.

Dormant Willow Post Method

Roseboom (1995) reported that for bioengineering work on a 600-ft reach at Court Creek, Illinois, it took 5 men two 8-hr days to install 675 willow (12- ft tall) posts on 4-ft centers. This also included installation of a rock toe (20 tons of 10" riprap) with a coir geotextile roll along 300 ft. Also, 60 cedar trees were laid and cabled along the toe of the slope to trap sediment. This included an excavator operator along with the 4 other men previously mentioned. This equates to about 17 posts per man-hour that includes harvesting and installing the willow posts plus the other operations mentioned above, e.g., shaping site, cedar tree installation.

Vegetative Geogrid

Man-hour costs for 123 ft of a 6-ft high vegetative geogrid installed on the Upper Truckee River that was previously mentioned included the following:

Three days time of:

1 foreman/equipment operator

1 equipment operator

2 laborers

1 supervisor/project manager

Thus, 120 man-hours were expended on the above project assuming an 8-hr day. This equates to about 1 man-hour per linear foot of treated bank. About 66 percent of the costs of this treatment can be attributed to labor.

Standard Seeding

The cost for broadcast seeding per square meter can vary considerably according to some literature sources. Reported costs in man-hours per square meter vary from 0.004 (Kay 1978) to 0.07 (Schiechtl 1980) depending on the degree of slope and the type of seeds used.

Hydroseeding

Depending on the material used and the distance to adequate water, 4,000 to 20,000 sq. m can be hydroseeded by one hydroseeder machine per day (Schiechtl (1980). A hydroseeder normally uses a two-man crew.

Hydromulching

Mulching is often applied over seeds by a hydromulcher similar to a hydroseeding machine. For hydromulching or mechanical mulching without seeds, about 0.12 to 0.50 man-hours per square meter is estimated (Schiechtl 1980). Mulching after seeding increases the cost per square meter considerably. Hydromulching with a slurry of wood fiber, seed, and fertilizer can result in a cost of only 0.008 man-hour per square meter, according to calculations derived from Kay (1978), who reviewed contractor costs in California. The above man-hour calculations assume the following: use of a four-man mulching machine, seed and fertilizer applied at a rate of 0.75 ton per acre, and an application rate of 2 tons per hour.

Sprigs, Rootstocks or Plugs, Rhizomes, and Tubers

Costs for digging grasses and other herbaceous plants in their native habitat and transplanting propagules of these will vary depending on the harvesting system used, the placement of the plants, and the site. For digging, storing and handling, and planting 1,000 plants of sprigged wetland grasses and sedges, Knutson and Inskeep (1982) reported a rate of about 10 man-hours. Sprigs of this type were placed on 0.5-m centers, which would cover 250 sq. m. For the same kinds of plants, Allen, Webb, and Shirley (1984) reported a rate equivalent to 400 plants per 10 man-hours for digging, handling, and planting single sprigs. According to Knutson and Inskeep (1982), using plugs of any species (grass or forb) is at least three times more time-consuming than using sprigs (30 man-hours per 1,000 plugs).

Bare-root Tree or Shrub Seedlings

Depending on type of plant and local conditions, the reported costs of planting vary considerably. On good sites with deep soils and gentle slopes, the authors have experienced planting up to between 100 and 125 plants per man-hour. Logan et al. (1979), however, estimated that only 200 to 400 plants per day per person could be achieved on sites like the banks of the upper Missouri River.

Ball and Burlap Trees or Shrubs

Planting costs for this type of transplant will range from 10 to 25 plants per man-hour (Schiechtl 1980).

Containerized Plantings

The cost of plantings varies depending on plant species, pot type, and site conditions. By using pots other than paper, 20 to 40 plants per man-hour can be planted. With paper pots, up to 100 plants per man-hour can be planted (Schiechtl 1980). Logan et al. (1979) stated that the cost for hand-planting containerized stock ranges from one-half the cost for bare-root seedlings to a cost equal to or exceeding container seedlings.

TABLE 6.11 Streambank Erosion Protection Measures Relative Costs And Complexity

Measure	*Relative Cost*	*Relative Complexity*
Live stake	Low	Simple
Joint planting	Low	Simple
Live fascine	Moderate	Moderate
Brushmattress	Moderate	Moderate to Complex
Live cribwall	High	Complex
Branchpacking	Moderate	Moderate to Complex
Conventional vegetation	Low	Simple to Moderate
Conventional bank armoring (riprap)	Moderate	Moderate

Available resources

Available resources fall in these four categories, one or more of which will be the critical constraint for a specific project:

- Funds,
- Labor,
- Materials, and
- Equipment.

The availability of funds is often the greatest constraint on selection of techniques. The most economical project is more difficult to design than one that is merely effective. A lack of funds can sometimes be overcome if the local situation is such that volunteer or low-wage labor is available. Ingenious use of locally available materials can sometimes compensate for a lack of funds. Equipment availability will not be a factor for projects to be advertised for construction on the open market in an area that supports contractors with general construction capability. Contractors earn their living by using their equipment efficiently and are probably more competent to identify equipment requirements than the engineer. However, for projects to be constructed by the sponsor's forces or another specific party, the choice of techniques may be more restricted. The team should consult with the appropriate construction personnel early in the planning stage to eliminate impractical techniques.

Feasibility of incremental construction

The cost of a stabilization project can sometimes be reduced by incremental construction, using one of two approaches. The first approach is to select a method for the first phase that will induce deposition, and for the next phase a method which takes advantage of the deposition to reduce total cost. This approach requires flexibility in funding and timing of construction, but is very useful and economical in some cases. It can reduce the required height of retards and retaining structures, and permit the planting of vegetation at the ideal season for growth and at the ideal time to take advantage of induced deposition and to induce more deposition. It also spreads the expenditure for construction over a longer period of time.

The second approach does not generally decrease total cost, but expenditures will be spread over a longer period. This approach is to initially stabilize only the portion of bank that is the highest priority, and to stabilize the remainder on a delayed schedule which ultimately accomplishes the project purpose. This approach is common on comprehensive projects and it can be used with most stabilization techniques, but requires a reliable forecast of channel migration. A variant of this approach is to use initial stabilization works to generate a change in the physical character of the stream that will enhance the use or construction of subsequent works.

Practicality

It should go without saying that the alternatives should be evaluated for practicality. If the selected technique is not constructable or the materials are unavailable then the approach is of no value.

Material Availability

Generally speaking, materials for most restoration efforts are attainable - but their general availability will greatly influence project cost. Vegetation used in restoration projects is often more difficult to obtain than are inert materials, and planning for vegetation acquisition is critical. This is discussed in detail below.

Constructability

Planners and designers of restoration projects seem to have the uncanny ability to select alternatives that are exceedingly difficult to "put in the ground". Most do not have a construction background and, thus, are generally unaware of limitations in equipment capabilities and safe operating procedures. Contractors are forced to significantly increase bids to accommodate uncertainties and difficulties in construction when often a relatively minor modification to the plans would permit safe construction using commonly available equipment. Many contractors are excluded from bidding a project simply because its installation requires specialized practices or equipment not generally available. This reduces competition and increases project costs.

Heavy equipment likely to be used for restoration projects includes backhoes, excavators, crawler tractors, crawler loaders, motor graders, wheel loaders, rough terrain forklifts, compaction equipment, water trucks, water trailers, water towers, skid loaders, loader landscaper, tractors, and dump trucks. Designers and planners should investigate equipment and contractor availability and understand the specifications and operating capabilities of the equipment likely to be used. A typical backhoe-loader, for example, weighs about 7 tons, has a 75 in wheelbase, a 1 cy. hoe bucket, a 6.5 cy. loader bucket, and can effectively work only about 15 ft from the machine with the hoe.

Evaluating Alternative Performance

The purpose of evaluating a riverine ecosystem restoration or mitigation project is to help a decision-maker identify and select appropriate management measures. Selected measures are generally those most likely to provide the greatest ecological benefits at the lowest cost, an especially important consideration in an era of budgetary constraints and enormous environmental challenges. In some cases, the “greatest” ecological benefit is not the objective, but rather a specific, quantified environmental or ecological benefit is sought. In either case, tools are needed to help the project team evaluate the impacts of proposed management measures, predict future ecosystem conditions, and interpret results.

Impact Identification Methods

There are four principal methods for identifying environmental effects and impacts: checklists, matrices, flow diagrams, and modeling.

1. Checklists. Checklists are comprehensive lists of environmental effects and impact indicators designed to stimulate the analyst to think broadly about possible consequences of contemplated actions. This strength can also be a weakness, however, because it may lead the analyst to ignore factors that are not on his lists. Checklists are found in one form or another in nearly all environmental impact assessment methods.

2. Matrices. Matrices typically employ lists of management measures and impact indicators related in a matrix which can be used to identify (to a limited extent) cause-and-effect relationships. Published guidelines may specify these relationships or may simply list the range of possible actions and characteristics in an open matrix, to be completed by the analyst.

3. Flow diagrams. Flow diagrams are sometimes used to identify action-effect-impact relationships. The flow diagram permits the analyst to visualize the connection between action and impact. The method is best suited to single project assessments, and is not recommended for large regional actions. In the latter case, the display may sometimes become so extensive that it will be of little practical value, particularly when several action alternatives must be examined.

4. Models. With the advent and increasing use of computer technology, analytical models have availed themselves to the analyst, and have fast become the method of choice for assessment of environmental impacts. Models are most frequently used to predict environmental variables related to hydrology, hydraulics, sediment transport and substrate composition, soil stability, and structure performance. However, a few analytical ecosystem and habitat models have emerged in recent years. Included in this category are the uses of spatial data analysis techniques employing geographic information systems.

Methods for Prediction

Methods for prediction cover a wide spectrum and cannot readily be categorized. All predictions are based on conceptual models of how the universe functions, they range in complexity from those that are totally intuitive to those based on explicit assumptions concerning the nature of environmental processes. Provided that the problem is well formulated and not too complex, scientific methods can be used to obtain useful predictions, particularly in the biogeophysical disciplines. Methods for predicting the behavior of *qualitative* variables are difficult to find or to validate. In many cases, the prediction consists of indicating merely whether there will be degradation, no change, or enhancement of environmental quality. In other cases, qualitative ranking scales (from 1 to 5, 10 or 100) are used. Some *quantitative* techniques (generally models) exist that are geared toward assigning specific values to habitat. Others asses key environmental variables which are in turn evaluated either quantitatively or qualitatively for their ecological significance.

Because some methods are better or more relevant than others, a listing of recommended methods for solving specific environmental problems would seem to be desirable. However, a compendium of methods, even with numerous footnotes and words of caution, is likely to be a snare for the unwary non-specialist. The environment is never as well behaved as assumed in models, and the assessor is to be discouraged from accepting off-the-shelf formulae. Generally speaking, some modeling technique(s) will be required to predict impacts and benefits of proposed activities. Depending upon the type of project, predictive accuracy requirements, and scope of the project, one or more of the several types of models may be warranted.

1. Deterministic and probabilistic models In the former, all the relationships are assumed to be defined by physical laws. In the latter, some, or all, of the relationships can only be defined in terms of statistical probabilities.

2. Linear and non-linear models Although it may be convenient to assume that relationships between variables are linear, most practical problems require the more complex assumption of non-linearity.

3. Static and dynamic models Static models are independent of time, while dynamic models have "time", with its characteristic property of being able to change in only one direction, as a major variable.

4. Predictive and decision-making models Predictive models enable the consequence of particular decisions to be explored, while decision-making models indicate which of the decisions is "best" in some defined way.

Methods for Interpretation

The nature and extent of impacts associated with various management measures generally require further interpretation to determine if they meet the project objectives or if they are the "best" alternative to meet those objectives. Management measures frequently impact more than the target variable and these impacts must be assessed. There are four methods for interpreting the results of impact analyses and for obtaining composite indices: a) display of sets of values of individual impact indicators, b) ranking of alternatives within impact categories, c) normalization and mathematical weighting, and d) absolute value determination.

1. Display Sets. One way to avoid the problem of synthesis is to display all the impact indicators in a checklist or matrix. For a relatively small set and provided that some thought is given to a sensible grouping of similar kinds of indicators into subsets, a qualitative picture of the aggregate impact may become apparent by the clustering of check-marks in the diagram. This approach is used in numerous methods. Because the assessor wishes to be all-inclusive, however, the sets are usually much too large for visual comprehension. In the Leopold matrix, for example, 17,600 pieces of information are displayed. Such an array may confuse the decision-maker, particularly if a separate check-list or matrix is prepared for each alternative.

2. Ranking of Alternatives within Impact Categories. A second and better method for estimating relative importance is to rank alternatives within groups of impact indicators. This permits the determination of alternatives that have the least adverse, or most beneficial, impact on the greatest number of impact indicators. No formal attempt is made to assign weights to the impact indicators; hence the total impacts of alternatives cannot be compared.

3. Normalization and mathematical weighting. In order to compare indicators numerically and to obtain aggregate impacts for each alternative, the impact indicator scales must be in comparable units and an objective method for assigning numerical weights must be selected. Various normalization techniques are available to achieve the first objective. In the PHABSIM, for example, habitat value is scaled from 0 (very bad) to 1 (very good). "Very bad" and "very good" can be defined in various ways. For quantitative variables such as water or air quality, "very bad" could be the maximum permissible concentrations established by law, while "very good" could be the background concentrations found at great distances from sources. A method of weighting may be required in order to obtain an aggregate index for comparing alternatives. This is undoubtedly a controversial part of the analysis. The following schemes are listed in increasing order of complexity: a) count the numbers of negative, insignificant and positive impacts, and sum in each class, b) when the impact indicators are in comparable units, assign equal weights, c) weight according to the numbers of affected persons, and d) weight according to the relative importance of each impact indicator.

4. Absolute Value Determination. In some cases, it may be possible to define absolute values of environmental quality. The Habitat Evaluation Procedure (HEP) provides a mechanism to accomplish this objective. For example, on the UYP (discussed later as a case study), waterfowl habitat was assigned an absolute value by formulating an index (Duck-Use-Days) based upon the forage requirements of waterfowl and the caloric benefits of various types of vegetative cover. Absolute value determinations permit a one-to-one comparison of mitigation alternatives and impacts with limited bias. However, they are data- and analysis-intensive and are often beyond the scope and budget of water resources restoration projects.

Permit Requirements

Contact Your Local Government - Local ordinances and State laws often prescribe construction practices, BMPs, materials, and other requirements for riparian and stream restoration efforts. Before beginning any work, contact your local government regarding erosion and sedimentation to determine necessary procedures for the approval of the project and obtain guidance for protecting the stream during construction.

Contact the US Army Corps of Engineers - to determine whether a permit will be needed for your construction activity. In most cases, minor streambank restoration is already covered by a general permit.

Other Planning Considerations

Locate Underground Services Which Could Be Affected by Construction Activities - Sewer lines, underground utilities, wells, septic tanks and drainfields, etc.

Determine Access and Clean up Cost - Be sure to consider access to the stream for machinery and vehicles onto your property and possibly your neighbors'. Typically, due to various site elements such as existing landscaping, irrigation systems, etc., urban sites have major access considerations. The costs for repairing construction damage also needs to be calculated.

Develop a Safety Plan - You may be working with power tools in wooded areas and adjacent to flowing and, sometimes, deep water. Have appropriate safety devices such as goggles, leather work gloves and chaps for chain saw use. Consider insect and snake hazards, and avoid deep or stormwater flows.

Protect the Water Resources - Take steps to ensure that soil does not get pushed or washed into the stream during this project. Install and maintain sediment control devices where needed.

Define Reasonable Project Limits - Begin and end all streambank protection projects at stable points along the bank. This may be a point at which the main thrust of the flow is parallel to the bank, or at a stable structure such as a bridge or culvert. This may require cooperative efforts by several landowners.

Control Runoff - Divert intensive sources of runoff such as gutter downspouts or street drainage away from the area to be treated, and be sure to include appropriate drainage facilities for this flow.

Monitor Site Changes - Planning often takes considerable time and site conditions may change in the interim between the field reconnaissance and the design. Be sure to periodically monitor the site to identify changes that might affect the final design.

Early Planning for Plant Material Acquisition

Prior to the implementation of the project, the plans for acquiring plants must be made well in advance (sometimes 1 - 2 years). To select vegetation for the project, vegetation existing on or near a site and on similar nearby areas which have revegetated naturally are the best indicators of the plant species to use. If commercial plant sources are not available (USDA, Soil Conservation Service, 1992), then on- or off-site harvesting can be considered. When acquiring plants, care must be given to local or federal laws prohibiting such plant acquisition and decimating the natural stands of wetland plants. Additionally, care must be taken to assure that pest species, such as purple loosestrife, are not collected and transferred to the project site.

The availability of plants of the appropriate species, size, and quality is often a limiting factor in the final selection and plant acquisition process. Some native plant species are very difficult to propagate and grow and many desirable species are not commonly available in commerce, or not available as good quality plants. As demand increases and nurserymen gain more experience in growing native plant species, this limitation should become less important (Leiser, 1992). Plant species composition and quantity can often be determined from the project objectives and functions desired. As a general rule, it is advisable to specify as many species as possible and require the use of some minimum number of these species. Maximum and minimum numbers of any one species may be specified.

Native Plant Material Collection

Some native plant species have adapted to a variety of geographic areas, edaphic conditions and micro-environments. Locally adapted plant populations (i.e. ecotypes) are best suited for use in habitat restoration projects. Planting stock of inappropriate origin (i.e. adapted to a different environment) is likely to lower plant survival rates and jeopardize project success.

It is important to avoid contaminating the gene pools of natural areas near your revegetation site. The use of locally-collected propagules for native plant revegetation projects maintains the integrity of the local gene pool. This is especially important when restoring sensitive habitats, reintroducing rare plant species and when working with plants which hybridize easily. Most native plant nurseries are willing to contact grow locally-collected plant materials for your habitat restoration project. Their nursery staff will come to your area to collect the necessary propagules (e.g. seeds, cuttings) and/or will advise you on the proper collection methods and timing.

Additionally, certified nurserymen keep accurate records of the origins of the native plants which they have in their inventory. Thus, in the event you cannot wait the required amount of time for the contract growing of site specific plant materials you may be able to obtain suitable native plants from one or more of the native plant nurseries in your region.

- Whenever possible collect plant propagules from either on-site or suitable areas close to your restoration site.

- If at all possible collect plant propagules from donor plants growing in the same watershed as your restoration site.
- Match the collection site with your restoration site for: elevation, soils, slope, aspect, rainfall, annual temperature patterns, frost dates, and associated vegetation.
- Know proper species identification.
- Avoid donor plants of unknown origin (e.g., garden escapes).
- Avoid collecting materials from isolated stands or individuals as they may diminish genetic variability.
- Collect seeds at their proper stage of ripening (i.e., mature seed).
- Avoid collecting from plants growing near non-local (e.g. landscaping, garden escapees) plants of the same species to prevent future contamination (hybridization).
- Avoid collecting from unhealthy or atypical plants.
- Collect equal amounts of propagules from suitable donor plants.
- Collect from at least 50 individual donor plants of the same species; especially when phenotypic variation (i.e., genetically visual variations in species appearance) is prevalent.
- Collect from widely spaced donor stands.
- Do not over collect; collect <10% of seed available.
- Contact both the Department of Fish and Game and the U.S. Fish and Wildlife Service before collecting propagules from rare plant populations.
- Obtain any required permit(s) before collecting wetland plant materials.
- Properly label collection bags.

7 DESIGN

Chapter Overview

This chapter presents two general design procedures for stream restoration projects and discusses the relative merits of each. In general, each project will require some combination and/or adaptation of the techniques presented, so these are intended as a general guideline only.

Specific design details for a few aspects of stream restoration projects are also presented. Given the wide array of features that can become a part of a restoration project, the presentation of design criteria for each would rapidly consume all the resources applied to the preparation of this handbook and the resulting document would collaborate with gravity to prevent its removal from the printer. Thus, only a few of the more common restoration elements are presented.

General Design Considerations

No “standard" procedure has been established for the design of stream restoration projects. As was mentioned in Chapter 1, restoration designers engage in one of three general approaches to achieve functional objectives and dynamic equilibrium for stream restoration projects:

1. *Self-recovery*: where stresses causing degradation can be removed and the stream ecosystem will recover of its own accord within an acceptable time frame. In such cases, a forced design is unnecessary and may be detrimental.
2. *Assisted recovery*: where a stream ecosystem may recover on its own, but slowly or uncertainly. In these cases, designs should facilitate natural processes and partial self-recovery.
3. *Full restoration*: where the degradation is beyond the repair capacity of the ecosystem and assisted recovery will result in incomplete, unstable, or undesirable form or functions.

Each of these approaches requires a different design procedure. Furthermore, the various agencies that undertake restoration projects operate under differing mandates (including policies and regulations) that impact, to some degree, the tools used for environmental evaluation and project design, but the specific steps in the process vary. Generally speaking, the level of sophistication and effort in the assessment and design is a function of the scale of the project.

A typical approach to stream restoration can be summarized in six steps:

1. Characterize the existing ecosystem (physical, chemical, biological, and sociological) and identify factors that limit natural function.

2. Work with project sponsors to formulate ecologically- and socially-based project objectives.
3. Assess the form and function of the system and predict future conditions.
4. Formulate alternatives for the achievement of the project objectives and evaluate these to identify preferred alternatives.
5. Develop the full restoration design and assess the future with-project condition and formulate a monitoring and maintenance plan.
6. Implement the plan, monitor, and maintain.

Imbedded within this six-step process are many additional requirements, and the level of detail in the analyses varies with the project scope, system complexity, and other factors. Implicit in the entire process are the attainment of the project objectives with a minimum of disruption to existing aquatic and terrestrial habitats and the formulation of a plan that will result in a naturally-functioning dynamically-stable channel. Because few, if any, people possess the broad knowledge needed to effectively formulate complete restoration plans, the approach is typically applied by a team with a diverse technical and professional background.

Steps 3 through 5 frequently involve analytical computations to assess hydraulic and hydrologic character, habitat conditions, channel stability, and performance of proposed environmental features. These steps are the nucleus of the design effort.

Alternate Approaches

Successful stream restoration projects are usually the result of carefully negotiating the best possible outcome for the project site given the prevailing knowledge of the ecosystem, restoration constraints, and the diverse interests of stakeholders. Thus, restoration success depends as much upon the process as it does upon the product. No one process will work effectively in all situations, so the design team should be prepared to adapt the procedures used to fit the situation.

Two fundamentally different approaches to developing restoration designs can be identified:

- *The Reference Approach:* A “target” or “reference” stream is identified and its physical characteristics are copied directly or are scaled to fit the project reach.
- *The Analytical Approach:* Requirements for specific functions (habitat needs, for example), the fundamental equations of continuity and motion, and other physical relations such as regime equations are used to compute the necessary physical characteristics of the project reach.

Each fundamental approach benefits from including components of the other, so hybrid approaches are most commonly used. Table 7.1 presents the fundamental principles, applicability, and limitations of each approach.

Both approaches include (or should include) a watershed assessment as the first step. A watershed analysis is needed to ascertain the existing condition of the system and factors that may have contributed to the channel degradation. This includes evaluating historic changes in the vegetation, location, development, and other landscape and vegetative changes that affect the magnitude and duration of peak and base flows, and the yield and character of sediments introduced from bank and bed erosion, landslides, roads and construction sites, and surface runoff.

Table 7.1 Contrasts between the reference and analytical design approaches.

Issue	*Reference Approach*	*Analytical Approach*
Fundamental Principles	Naturally stable channels exhibit characteristics that are consistent in their dimension, pattern, and profile. Parametric descriptions from a reference reach can be extrapolated and used as a template for the modification of impacted reaches in other hydro-physiographic provinces.	The fundamental laws of conservation of mass and momentum govern channel character. Given knowledge of the character of the hydrology, sediment yield, channel boundary conditions, and project objectives, the requisite physical characteristics of the project reach can be determined computationally.
Data Requirements	A suitable reference reach. Measurements of the physical characteristics of the reference reach and its watershed, as well as for the project reach and watershed. Hydrologic analyses.	Varies with project, but may include: Detailed site survey to characterize physical conditions of project reach. Hydrologic and hydraulic analyses. Analyses of sediment yield, sediment transport, and bed and bank stability. Suitable algorithms for computational methods.
Application/ Limitation	Best suited to small-scale projects in low-impact watersheds where the stress causing degradation is no longer present. Cannot address future changes. Inexpensive, quick, easy to understand.	Broadly applicable and necessary on large-scale or complex projects. Can be used to evaluate changes in watershed or channel conditions. Can be data intensive, expensive, and slow, depending upon the scope of the project and data availability.

The remaining steps of the reference approach can be summarized as follows:

2) Identify project and reference reaches and undertake a morphological characterization and classification of each;
3) If the project and reference reaches are of a different scale, locate gage stations in similar hydro-physiographic provinces, use bankfull indicators and field measured data to classify these reaches, and develop basin hydrology and regional curves;
4) Using the reference reaches as a template and regime data from regional sources, develop a preliminary design for the cross section and planform of the project reaches;
5) Formulate the profile using the reference reaches as a template; and
6) Lay out the proposed design and adjust to conform to existing landscape features.

The analytical approach can follow any number of steps, depending upon the availability of data, scope of the project, and experience of the designer. One approach advocated by the US Army Corps of Engineers follows these steps:

2. Calculate a stable channel slope and depth. This step insures that channel geometry is capable of transporting the inflowing sediment load through the project reach. Analytical approaches calculate the design variables of width, slope, and depth from the independent variables of discharge, sediment inflow, and bed-material composition. Three equations are required for a unique solution of the three dependent variables. Flow resistance and either incipient motion or sediment transport equations are readily available to determine the range of potential stable slopes and corresponding channel geometry. This technique does not provide a unique solution, and a third equation is necessary to solve for at least one cross section variable.

3. Determine the design width of the channel. The design width is related to the idealized "bankfull width" which is the channel top width that occurs when the channel-forming (dominant) discharge occurs. In terms of frequency this discharge generally varies between the 1.5 and 2 percent chance exceedance annual peak flow, but may be outside this range. Current research suggests that the effective discharge is the best representation of the channel forming discharge. The effective discharge is the increment of discharge that transports the most sediment on an annual basis. This discharge may be determined by integrating a sediment transport-rating curve with the annual flow-duration curve. This calculation requires a knowledge of the flow-duration characteristics, bed material size distribution, and a sediment rating curve (either measured, calculated, or a combination thereof). This channel-forming discharge can sometimes be verified with field indicators of bankfull discharge.

Several techniques are available for determining the design width as a function of the channel-forming discharge in stable alluvial streams. In order of preference they are:

a. Develop a width vs. effective discharge relationship for the project stream. This can be accomplished by measuring average width in stable reaches where the effective discharge can be calculated. These channel reaches may be in the project reach itself or in reference reaches upstream and/or downstream from the project reach. If there is no significant lateral inflow and if a stable reach can be found within the project reach, then a single measurement may be sufficient. This also assumes that the banks are composed of similar material (and similarly vegetated) in the project and reference reaches and that there are no significant hydrologic, hydraulic, or sediment differences in the reaches. This technique is inappropriate for streams where the reference reaches are unstable.

b. Find stable reaches of streams with similar hydrologic, hydraulic, and sediment characteristics in the region and develop a hydraulic geometry relationship for width vs. effective discharge. This technique is also inappropriate for streams where the reference reaches are unstable.

c. If a reliable width vs. effective discharge relationship cannot be determined from field data, analytical methods discussed in step 2 may be employed to obtain a range of feasible solutions. If the channel width is constrained due to right of way limits, select the required width and be prepared to provide bank protection.

The composition of the bank is very important in the determination of a stable channel width. It has been shown that the percentage of cohesive material in the bank and the amount of vegetation on the bank significantly affect the stable channel width. General guidance is available in U.S. Army Engineer Manual EM-1110-2-1418 (1994). Currently under development at WES are hydraulic geometry predictors for various stream types with different bank characteristics. These predictors will include confidence limits and may be used for general guidance when site specific data cannot be obtained.

4. Determine a stable channel meander wavelength, l. The most reliable hydraulic geometry relationship for meander wavelength is wavelength vs. width. As with the determination of channel width, preference is given to wavelength predictors from stable reaches of the existing stream either in the project reach or in reference reaches. Lacking data from the existing stream, general guidance is available from several literature sources.

5. Calculate the channel length, L, for one meander wavelength. Given the meander wavelength, λ, the channel slope, S_o, and the valley slope, S_v, the channel length is computed from:

$$L = l\left(\frac{S_0}{S_v}\right)$$

6. Layout a planform using the meander wavelength as a guide. One way to accomplish this task is to cut a string to the appropriate channel (meander) length and lay it out with the appropriate wavelength on a map. Another, more analytical approach, is to assume a sine-generated curve for the planform shape and using the algorithms described by Fischenich (1996). This numeric integration can be accomplished using a computer program such as the one in the SAM hydraulic design package. The sine-generated curve produces a very uniform meander pattern. A combination of the string layout method and the analytical approach would produce a more natural looking planform.

Check the design radius of curvature to width ratio, making sure it is within the normal range of 1.5 to 4.5. If the meander length is too great, or if the required meander belt width is unavailable, grade control may be required to reduce the channel slope.

7. Conduct a sediment impact assessment. The purpose of the sediment impact assessment is to assess the long-term stability of the restored channel in terms of aggradation and/or degradation. This can be accomplished using a sediment budget approach for relatively simple projects or by using a numerical model that incorporates solution of the sediment continuity equation for more complex projects. With a sediment budget analysis, average annual sediment yield with the design channel is compared to the average annual sediment yield of the existing channel. Large differences in calculated sediment yield indicate channel instability. It may be necessary to design a channel that is less than ideal in terms of channel stability in order to achieve flood control or habitat benefits. Typically, a compound channel design provides the best combination of benefits.

The most reliable way to determine the long-term effects of changes in a complex mobile-bed channel system is to use a numerical model such as HEC-6. River systems are governed by complicated dependency relationships, where changing one significant geometric feature or boundary condition affects other geometric features and flow characteristics both temporally and spatially. Changes at any given location in a stream system are directly related to the inflow of sediment from upstream. This makes the application of the sediment continuity equation essential to any detailed analysis. The most significant of these relationships and the continuity of sediment mass are accounted for in the numerical model approach.

The analytical approach can benefit in several ways from the incorporation of reference information. First, the process of selecting a reference reach is very beneficial in establishing project objectives and getting the design team "on the same page," particularly in terms of a visual framework for the project. Second, reference data provides valuable insight into the acceptable and desirable variability in channel character for the project.

Likewise, the reference approach benefits from the inclusion of the physical and biologic assessments that are incorporated in the analytical approach. Lacking these, the success of a restoration project is dependent not only upon the skill of the team in selecting an appropriate reference, but also on a good deal of luck.

Reference Reaches

A reference reach that is used for restoration design should be evaluated to make sure that it is stable and has a desirable ecological condition. In addition, the reference reach must be similar enough to the desired project reach that the comparison is valid. It must be similar to the desired project reach in hydrology, sediment load, bed and bank material, width, depth, history, and slope. If the reference reach is substantially different than the project site (for example, if the slope of the reference reach is steeper than the project reach), then the designer needs a good method of scaling the different geometry of the reference reach to fit the project reach. For this to be done using hydraulic geometry relations alone, one would need a statistically valid curve applicable to the sites in question. The results obtained by the use of hydraulic geometry relations alone can be used for planning and preliminary design, but are not recommended for final design of large or complex restoration projects. Site-specific hydraulic and sediment analyses are often cost-effective tools for preliminary design in those cases, and are recommended for final design. An examination of the geomorphology and ecology of a reference reach is recommended to be assured that the goals for the project reach are appropriate.

The term "reference reach" has several different meanings, leading to confusion in the use of the term. As used above, for the design of a stable (equilibrium) stream channel in a restoration project, it is a reach which will be used as a template for the geometry of the restored channel. The width, depth, slope, and planform characteristics of the reference reach are transferred to the design reach, either exactly, or using analytical or empirical techniques to scale them to fit slightly different characteristics of the project reach (for example, a larger or smaller drainage area). If the reference reach is to be used in this manner, the ability to transfer features to the project reach must be carefully considered. Not only will riparian infrastructure present limiting conditions, but conditions of the reference reach which evolved over time such as soil compaction and rooting depths should be considered.

A second common use of the term "reference reach" is that of a reach with a desired biological condition, which will be used as a target to strive for when comparing various restoration options. For instance, for a stream in an urbanized area, a stream with a similar drainage area in a nearby “unimpacted” watershed might be used as a reference reach, to show what type of aquatic and riparian community might be possible in the project reach. Although returning the urban stream to pre-development conditions may not be achievable, the characteristics of the reference reach can be used to indicate what direction to move toward. In this use of the term, a reference reach defines desired biological and ecological conditions, rather than stable channel geometry. Tools such as FIS(H), IFIM and RCHARC can be used to determine what restoration options come closest to replicating the habitat conditions of the reference reach (although none of the options may exactly match it).

Materials

A quick but thorough evaluation of the local availability and cost of materials commonly used for restoration and stabilization projects should be conducted by the designer. Though manufactured materials such as coir fabric can be shipped anywhere, restoration projects rely heavily upon natural materials that are obtained near the project site. Vegetation propagules, boulders, armor stone, trees, etc., are seldom shipped any distance and must be found locally in suitable quantity to be used cost effectively. The quality of available materials should also be investigated prior to the design development to ensure that they will meet the design requirements. Techniques requiring materials that cannot be readily obtained, have excess cost, or are of inadequate quality should be eliminated from consideration immediately.

Construction Techniques

Another factor that significantly affects the design is the constructability of the project. The designer should always consider the type of equipment a contractor will require, the staging and sequencing of construction, and operating safety when developing the design. The use of specialized equipment or construction practices that deviate from the norm will add significantly to the project cost. In addition, projects that require materials and techniques with which the contractor are familiar are more likely to be installed properly than those that the contractor must learn "on the job". Timing of construction and the weather and flow conditions are also factors that sometimes dictate the construction requirements and design features.

Modifying the Preferred Alternative

After the preferred alternative is selected following the suggestions in the preceding chapters, it is a good idea to review the project objectives to determine if minor modifications to the preferred alternative can improve the project's environmental function. Dardeau and Fischenich (1994) modified a design for a flood control project to incorporate environmental features into the design, saving $16M in project costs by reducing mitigation requirements through the relocation of borrow pits, levee realignment, modified interior drainage, and incorporation of habitat features into the design. Table 7.2 provides considerations for environmental features associated with bank stabilization projects.

Table 7.2. Environmental features for channel side slope protection (after Genetti, 1989).

If you wish to:	Consider using:
Maintain or improve terrestrial riparian habitat value	reinforced revetment, toe protection, bank sloping and revegetation, vegetation, stream corridor management, fencing and buffer strips, or floating plant constriction
Provide stable substrate for benthic macro-invertebrates	riprap or quarry run stone, gabions, or hard points
Provide or maintain fish habitat	tree revetments, earth core dikes, hard points, tree retards
Improve or maintain aesthetic resources	vegetation, combinations of vegetation and structures (composite revetment, earth core groins, excavated bench, and revegetation of riprap), fencing and buffer strips, selective clearing
Provide access to stream for recreation and/or wildlife	composite revetment, berm preservation and restoration, bank sloping and revegetation, channel relocation, revegetation of riprap, or stream corridor management

Bank Stabilization Design Criteria

Excavation and Fill

Standard techniques, designs, and specifications for excavation and fill generally apply to restoration and stabilization projects, with one exception. Fill material placed along the face of a bank must be more freely draining than the parent material in the bank. One of the more common mistakes in bank stabilization projects is the reshaping of banks using a cut and fill technique to reduce bank slope. Although flatter slopes are generally more stable than steep slopes, the cut and fill technique often places poorly-drained soils over seepage horizons in the lower bank, leading to geotechnical instability. In addition, it may be difficult to stabilize disturbed material close to the water line.

Armor Stone Sizing and Design

Design guidance for revetments is well developed in both fluvial and wave attack environments and whatever the material used the probability of failure will be small provided that design criteria are followed rigorously. Experience shows that where revetments do fail, this can usually be attributed to excessive and unpredicted toe scour next to the revetment, flanking due to excessive bank erosion at either or both ends of the revetment, or geotechnical instability associated with deep-seated failure or adverse drainage in the bank. To guard against these dangers, it is important to load the toe of the revetment with a launching apron to prevent undercutting; to ensure that the revetment is sufficiently long to cover the entire reach of eroding bank; and to take great care over the design of seepage filters within the revetment to retain soil, but allow free drainage.

Increasingly, revetment is designed with vegetation as an integral component either for environmental or structural reasons. The appearance of almost any revetment can be improved using vegetation. Volunteer species tend not to be desirable and a pro-active approach in which seeded soil or living plants are introduced to the revetment are increasingly popular. In this respect, light revetments can almost be considered as a type of hybrid protection.

Problems do exist with vegetated revetments, however, and these must be borne in mind. Vegetation obscures the structure, making inspection much more difficult and the stems of woody species may breach the protective armor either through mechanical disturbance or through generating local turbulence during high flows. Usually, it is wise to limit vegetation on revetments to grasses, reeds and shrubs rather than trees, and pollarding, coppicing or removal of woody species is required. In this respect, the inspection and maintenance commitments for vegetated revetments are much greater than for unvegetated ones.

Guidance for riprap in streamflow applications is found in EM-1110-2-1601, "Hydraulic Design of Flood Control Channels," dated 1991 with Change 1 dated 30 June 1994. This guidance uses a procedure based on local depth-averaged velocity.

From EM 1110-2-1601 the equation for determining stone size is:

$$D_{30} = S_f C_s C_v C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5}$$

where

D_{30} =riprap size of which 30 percent (by weight) is finer, m
S_f = safety factor, unitless ($S_f \geq 1.1$)
C_s = stability coefficient for incipient failure, unitless
C_v = vertical velocity distribution coefficient, unitless
C_T = blanket thickness coefficient, unitless
d= local depth of flow, m
γ_w = unit weight of water, N/m^3
γ_s = unit weight of stone, N/m^3
V = local depth averaged velocity, m/s
g= gravitational constant, m/s^2
K_1 = side slope correction factor, unitless

Riprap thickness for most streambank protection projects is the greater of $1.0D_{100}$(max) or $1.5D_{50}$(max) and the blanket thickness coefficient (C_T) can be taken as 1.0. For riprap of this thickness and having a uniformity coefficient (D_{85}/D_{15}) between 1.7 and 5.2, the stability coefficient for incipient failure (C_s) can be estimated as:

$C_s = 0.30$ for angular rock
$C_s = 0.375$ for rounded rock

The value for the vertical velocity distribution coefficient (C_v) should be:

$C_v = 1.0$ for straight channels or inside of bends
$C_v = 1.25$ downstream of concrete channels
$C_v = 1.25$ at end of dikes

$C_v = 1.283 - 0.2\log(R/W)$ for outside of bends (or 1.0 for R/W > 26)

where:
R = centerline radius of bend, m
W = water surface width at upstream end of bend, m

Recommended side slope correction factors (K_1) based upon slope are shown in Table 7.3

Table 7.3 Side slope correction factors.

Slope	1V:1.5H	1V:2H	1V:3H	1V:4H or flatter
K_1	0.71	0.88	0.98	1.0

A minimum safety factor (S_f) of 1.1 should be used in all cases.

For bank protection $V = V_{SS}$ where V_{SS} is the depth averaged velocity at 20 percent of the slope length up from the toe. For natural channels typical of wetland applications, V_{SS} is determined from Figure 1 in EM 1110-2-1601 using average channel velocity, R, and W.

Scour Protection

Scour is the removal of soil particles by flowing water. While the entrainment of upland soils from overland runoff is included in this definition, scour on river systems generally refers to the removal of material from the bed and banks of the river from streamflow. Total scour on a river is composed of three components 1) General Scour, 2) Contraction Scour, and 3) Local Scour. In general, the components are additive when addressing scour on the streambed. The affects of scour are accounted for in the design of bank protection with the use of a key or launching section at the toe.The consequences of toe movement on the selected bank protection feature should be considered.

General Scour: The lowering of a river's bed elevation (also called bed degradation) over long reaches due to head cuts and changes in hydrology, controls such as dams, sediment discharge, or river geomorphology is termed general scour. General scour often occurs during the passage of a flood, but is sometimes masked because sediments deposit to the original lines and grades on the falling stage of the hydrograph. General Scour involves the removal of material from the bed and banks across all or most of the width of a channel. This type of scour may be natural or man induced, and requires geomorphic and sedimentation analyses to quantify. Analytical tools such as HEC-6 are helpful in evaluating long-term general scour. Estimates of ultimate scour can also be made using stable slope criteria or depths required for the formation of an armor layer.

Contraction Scour: The scour that results from the acceleration of the flow due to a contraction, such as a bridge, is called Contraction Scour. This type of scour also occurs in areas where revetments are placed such that they reduce the overall width of the stream segment. Contraction scour is generally limited to the length of the contraction, and perhaps a short distance up- and downstream, whereas general scour tends to occur over longer reaches.

Laursen's Equation (1960) given below is often used to predict the depth of scour in the contracted section. Laursen's Equation for a long contraction will overestimate the depth of scour at the upstream end of the contraction or if the contraction is the result of bridge abutments and piers. But at this time it is the best equation available. Note that the Manning n ratio can be significant in cases where sand bed channels have variable bed forms (e.g. a dune bed in the uncontracted reach and a plain bed, washed out dunes or antidunes in the contracted reach).

$$\frac{y_c}{y_a} = \left(\frac{Q_c}{Q_a}\right)^{6/7} \left(\frac{W_a}{W_c}\right)^{A} \left(\frac{n_c}{n_a}\right)^{B}$$

and

$$y_s = y_c - y_a$$

where

- y_s = scour depth (ft)
- y_a = average depth in the main reach (ft)
- y_c = average depth in the contracted section (ft)
- W_a= width of the main reach (ft)
- W_c= width of the contracted section (ft)
- Q_a= flow in the main reach (cfs)
- Q_c= flow in the contracted section (cfs)
- n_a = Manning n for main reach ($s/ft^{1/3}$)
- n_c = Manning n for contracted section ($s/ft^{1/3}$)

A and B are dimensionless transport coefficients, and can be obtained from Table 7.4:

Table 7.4 Dimensionless transport coefficients

V*/w	***A***	***B***
<0.5	0.59	0.07
1.0	0.64	0.21
>2.0	0.69	0.37

where

- V_*= shear velocity (ft/s), given by the relation - $(gyS_f)^{0.5}$
- ω = fall velocity of the D_{50} of bed material (ft/s)

Local Scour: The scour that occurs at a pier, abutment, erosion control device, or other structure obstructing the flow is called Local Scour. These obstructions cause flow acceleration and create vortexes that remove the surrounding sediments. Generally, depths of local scour are much larger than general or contraction scour depths, often by a factor of ten. Local scour can affect the stability of structures such as riprap revetments - leading to failures if measures are not taken to address the scour.

Factors that effect local scour include: 1) width of the obstruction 2) projection length of the obstruction into the flow; 3) length of the obstruction; 4) depth of flow; 5) velocity of the approach flow; 6) size of the bed material; 7) angle of the approach flow (angle of attack); 8) shape of the obstruction; 9) bed configuration; 10) ice formation or jams; and 11) debris.

Width of obstruction has a direct affect on the depth of scour - scour depth increases with obstruction width. Though not addressed by most empirical relations, the ration of obstruction width to the channel width is probably a better measure of scour potential than is the obstruction width alone.

Projected length of an obstruction into the stream affects the depth of scour. With an increase in the projected length of an abutment into the flow, there is an increase in scour. However, there is a limit on the increase in scour depth with an increase in length. This limit is reached when the ratio of projected length into the stream to the depth of the approaching flow is about 25.

The streamwise length of a structure has no appreciable affect on scour depth for straight sections but, when the structure is at an angle to the flow, the length has a very large affect. At the same angle of attack, doubling the length of a structure increases scour depth by as much as 33 percent. Some equations take the length factor into account by using the ratio of structure length to depth of flow or structure width and the angle of attack of the flow to the structure. Others use the projected area of the structure to the flow in their equations.

An increase in flow depth can increase scour depth by a factor of 2 or larger. For bridge abutments, the increase is from 1.1 to 2.15 depending on the shape of the abutment. Scour depth also increases with the velocity of the approach flow.

Size of the bed material affects scour depth, though the affect is generally a function of the time exposed to erosive flows. In other words, sediment size may not affect the ultimate or maximum scour but only the time it takes to reach it. Large particles in the bed material such as cobbles or boulders may armor plate the scour hole.

The angle of attack of the flow to an obstruction has a large affect on local scour, as does the shape of the structure. Structures angled such that they cause flow convergence increase scour whereas structures angled such that they cause divergence of flow lines generally decrease scour. Streamlining structures reduces the strength of the horseshoe and wake vortices, effectively reducing ultimate scour depths.

In streams with sand bed material, the shape of the bed (bed configuration) affects the turbulence and flow velocity which, in turn affect the depth of scour. Ice and debris can increase both the local and general (contraction) scour. The magnitude of the increase is still largely undetermined. But debris can be taken into account in the scour equations by estimating the amount of flow blockage (decrease in width) in the equations for contraction scour.

Two simple relations for estimating local scour depths along structures follow. Both have been modified by this author from research conducted by others. The first is based upon Laursen's (1980) approach for scour at a bridge abutment and the second upon Froehlich's (1987) equations for live-bed scour at bridge crossings. Guidance for computing local scour at the toe of a riprap revetment is also given in EM 1110-2-1601. These techniques are based on empirical approaches and have high errors of estimates.

Modified Laursen:

$$\frac{y_s}{y_a} = 1.3\left(\frac{Wo}{y_a}\right)^{0.48}$$

Modified Froehlich:

$$\frac{y_s}{y_a} = 2\left(\frac{\theta}{90}\right)^{0.13}\left(\frac{Wo}{y_a}\right)^{0.43} F_r^{\,0.61} + 1.0$$

where
y_s= Scour depth (ft)
y_a= Depth of flow at the structure (ft)
W_o= Length of structure projected normal to flow (ft)
θ = Angle of embankment to flow (deg.)
F_r= Froude number of flow upstream of abutment

The Modified Laursen equation is based on sediment transport relations. It gives maximum scour and includes contraction scour. FOR THIS EQUATION, DO NOT ADD CONTRACTION SCOUR TO OBTAIN TOTAL SCOUR AT THE STRUCTURE OR IN THE SECTION. The Modified Froehlich equation does not include contraction scour, but does include a safety factor (+1.0) that effectively accounts for contraction scour in most cases. Values computed from either method should be increased by $y_a/6$ for sand bed streams if dunes are the expected bed form.

Design Considerations

When designing a riprap section to stabilize a streambank, the author accounts for scour in one of two ways: 1) by excavation to the maximum scour depth and placing the stone section to this elevation, or 2) by increasing the volume of material in the toe section to provide a launching apron that will fill and armor the scour hole. Preference is generally given to option (2) because of ease of construction, cost and environmental impacts associated with excavation of the streambed.

The volume of material added to the toe section must be sufficient to armor to the ultimate depth of scour. The author uses a somewhat conservative approach that assumes that the side slope in the scour hole is 1:2 and that the requisite thickness of the launched armor layer should be twice the D_{100} of the riprap gradation. Thus, the volumetric increase in the size of the toe section is given by:

$$Vol = \frac{D_{100}\sqrt{5(y_s)^2}}{13.5}$$

where
Vol = The volume of riprap required (cy)
D100 = The largest size of stone in the riprap (ft)
Y_s = the estimated scour

Measures should be designed to provide against loss of support at the revetment's boundaries. This includes upstream and downstream ends, its base or toe, and the crest or top. Scouring of the foundation material by high velocity currents is a major cause of bank protection failure. In addition to protecting the lowest expected stable grade, additional depth must be provided to provide a footing that will not be scoured out during floods or lose its stability through saturation. Deep scour can be expected where construction is on an erodible streambed that possesses high velocity currents flow adjacent to it.

Extend the toe trench down to a depth below the anticipated scour and backfill with heavy rock. Anchor a heavy, flexible mattress to the bottom of the revetment, which at the time of installation will extend some distance out into the channel. This mattress will settle progressively as scour takes place, protecting the revetment foundation. Install a massive toe of heavy rock where excavation for a deep toe is not practical. This allows the rock forming the toe to settle in place if scour occurs. However, because of the forces of flow, the settlement direction of the rock is not always straight down. Drive a sheet piling to form a continuous protection for the revetment foundation. Such piling should be securely anchored against lateral pressures. To provide for a remaining embedment after scour, piling should be driven to a depth equal to about twice the exposed height. Install toe deflector groins to deflect high velocity currents away from the toe of the revetment. Install submerged vanes to control secondary currents.

The location of the upstream and downstream ends of revetments must be selected carefully to avoid flanking by erosion. Wherever possible, the revetment should tie into stable anchorage points, such as bridge abutments, rock outcrops, or well-vegetated stable sections. If this is not practical, the upstream and downstream ends of the revetment must be positioned well into a slack water area along the bank where bank erosion is not a problem, or bordered at the flanks by refusals.

Erosion Control Materials

Erosion control materials (ECMs) play an important role in many streambank restoration projects. ECMs include the wide variety of natural and synthetic fabrics, meshes and grids used to prevent soil erosion and reinforce vegetation. They fill a void between the erosion resistance of bare soil and that provided by a hard armor. If properly installed, and under the right circumstances, these materials can withstand relatively severe flow conditions. Many engineers have adopted the design procedures presented by the Federal Highway Administration (FHWA) in the most recent HEC #15 manual (1988). This design methodology utilizes maximum shear stress calculations in determining the suitability of various lining materials.

Manufacturer's performance data should be used in determining the suitability of an ECM for a project. This data is (or should be) the result of performance testing on the product installed as the manufacturer recommends. Therefore, to get the expected performance from each product, it's wise to specify "per manufacturer's published recommendations". The Texas Transportation Institute recently conducted testing of many ECMs and has available guidance for their application.

One of the more common types of ECM used in restoration designs are the temporary mats and fabrics intended to provide erosion protection only until vegetation can become well established and assume this function.

There are two distinct categories of temporary ECMs: photodegradable and biodegradable. Within those two categories is a wide range of products made from such natural fibers as straw, coconut (coir) fiber, wood excelsior, flax, and jute. The different fibers provide significantly different characteristics, features, and benefits. These ECMs are entirely degradable, meaning that biological organisms break down the fibers over time (biodegradable), or sunlight accomplishes the same objective (photodegradable).

The length of time required to break down these fibers depends on the amount of moisture and sunlight to which the fibers are subjected. In general, straw, excelsior, and jute erosion control products last for a shorter time period than do those made of coir or flax. Manufacturers indicate that some materials, such as straw blankets, will remain in recognizable form for only a couple months while others, such as coir-fiber blankets, remain for up to six years in good conditions. Projects using temporary erosion control products must be designed so that the vegetative component is well-established prior to the degradation of the ECM. A summary of the more common temporary ECMs follows.

Temporary Blankets. These products combine synthetic, photodegradable netting with fiber matrices and are primarily used for seedbed mulching. The most common blankets feature a mixed straw/coir fiber matrix sewn between a lightweight bottom net and a heavy- duty top net. The heavy-duty top net and addition of coconut fibers provide the blanket with greater durability, longevity, and effectiveness compared to straw, jute, and excelsior blankets.

Coir-Fiber Geotextiles. These products are nets or grids constructed from a loose coir fiber that is twisted into twine. The strength of a coir- fiber geotextile increases with the number of twines in either the warp or the weft or both. The open area of the coir geotextile decreases with the number of twines in the warp and weft. Because of their high tensile strength and relative durability, Coir-fiber geotextiles are used for a wide variety of restoration projects and for many different bioengineering techniques.

Prevegetated Coir-Fiber Mats. Prevegetated mats are loose coir-matrix mats in which emergent aquatic vegetation is grown hydroponically. They are similar to sod, and when containing mature plants can be 2 in. thick, 16.5 ft. long, and 3 ft. wide; weigh about 2 lb/ft, and are designed for use where velocities are low (generally less than 2 fps), or where wave heights are less than 1 ft, and slopes are less than or equal to 1:5. Roots have generally grown through the mat and are in direct contact with the soil when installed. The primary use of prevegetated mats is for projects that have a narrow planting window because of the date of installation.

Coir Geotextile Rolls

The coir geotextile roll (CGR) is a sausage-like roll of non-woven fibers made from coconut husks bound within a woven mesh rope either made from polyethylene or coir rope. The CGR incorporates wetland plants (usually as rooted sprigs or cuttings) whose roots become interlocked with the CGR fibers. The CGR with its plants is used along the face of an eroded streambank and acts principally to armor the bank, though it can also be configured to act as a current deflector. The CGR has the potential to accumulate sediment and, together with the plants, develop a strong network of interlocking roots and plant stems.

A site suited to a CGR requires a hydrological regime that 1) keeps the invert of the roll wet during most of the growing season; and 2) sustains flows sufficient to keep wetland plants growing well, but not so large of flows for long durations as to exceed the plants' flood tolerance. Given these requirements, streams best suited to CGRs are perennial, small to moderate in size, and have a relatively consistent water surface elevation associated with an extended baseflow.

The second most important factor in site selection is to choose a site that is not subject to massive amounts of sediment movement that could smother plants within the roll. CGRs have been effectively used, however, to trap soils from upper bank failures and establish conditions for subsequent colonization or planting. When thus used, planting should not be attempted until the upper bank has stabilized.

Other important considerations in site selection are: shade conditions, type of substrate in which they will be placed; and their relationship to the channel thalweg. Most wetland plants that are suitable for planting within a CGR are shade intolerant or at least require some partial sunlight. Therefore, the CGR, as a general rule, should be placed where some sunlight exists. There are exceptions where one can rely on shade tolerant plants, such as Baltic rush (*Juncus balticus)* or some species of burreed (*Sparganium* spp). It would be advisable to check with local USDA Natural Resource Conservation Service offices for other local shade-tolerant plants for the area of interest.

Substrate conditions are also important in site selection because the CGR must be securely anchored. If the substrate is non-cohesive material, such as sand or silt, anchoring may be problematic because of the lack of friction to hold the anchors in place. Conversely, if the substrate is laden with interspersed rock throughout or has a rock layer underneath the surface, this condition can adversely impact anchor penetration without special equipment or materials.

The CGR should also generally not be placed immediately adjacent to the thalweg. If it is, then one must bolster the CGR with stone to protect from scour and undercutting.

The primary design considerations for use of a CGR are: 1) elevation along the bank with respect to the hydrology of the stream; 2) sustained velocity and shear-stress thresholds that the CGR must withstand; and 3) toe and flank protection. Toe armor, i.e., rock, guards against undercutting of the treatment and flank hardening guards against currents working their way behind the treatment and causing it to fail from flanking.

Elevation of the CGR with respect to the stream's hydrology is of utmost importance. The CGR must be at an elevation to absorb water, but not so low in elevation as to subject the vegetation planted in it to complete submergence for a long period of time (> 21 days on average) during the growing season (fig. 7.1). Conversely, it must not be so high as to completely dry out and desiccate the planted vegetation. If stacked rolls are used, they must be in a position to be wetted quite often or to absorb ground water percolating from the bank. An exception to this requirement for periodic wetting is when willow whips or some other woody plant is used in between stacked CGRs as brush layers and have their basal end inserted well into a moist zone within the bank. In these cases, CGRs are intended primarily to provide temporary sediment and erosion control.

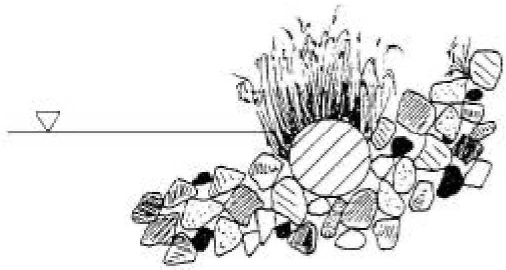


Figure 7.1. CGR shown at an appropriate elevation to sustain aquatic plant growth.

There have been few data collected for shear or velocity tolerances of the CGR. Available data come largely from empirical information or from vendors' design criteria (Table 7.5). Designers are urged to exercise caution in considering limiting velocity or shear stress criteria. Failure of CGRs can be attributed to several mechanisms, notably flanking, undercutting and anchor failure.

Table 7.5 Stress Type and Stress Levels for the CGR

CGR Type	Velocity	Shear
Roll with Coir rope mesh (staked only w/o rock bolster)	< 5 ft/sec	0.2-0.8 lb/ft^2
Roll with polypropylene rope mesh (staked only w/o rock bolster)	< 8 ft/sec	0.8-3.0 lb/ft^2
Roll with polypropylene rope mesh (staked w/ rock bolster)	< 12 ft/sec	>3.0 lb/ft^2

Protection to guard against undercutting and flanking the treatment is essential for success. For toe and flank protection, rock bolsters should be designed for velocities and shear stresses exceeding allowable limits for the soils underlying the CGR.

Flank protection can also be aided by keying the ends of the CGR into the banks at both ends and protecting it with a rock bolster. The ends should be keyed into the bank by inserting at least two linear feet of roll into the bank with rock on the upstream side, which is also keyed into the bank. For banks susceptible to significant erosion, keys or refusals should extend further into the bank.

Other design considerations include the configuration, e.g., one to several rolls, and size of rolls, e.g., 12, 16, and 20-in-diameter, needed to cover a streambank. Also, the length of bank-reach being eroded will determine the number of rolls needed. They normally come in 20-ft lengths, but can be custom tailored to fit certain situations if warranted.

Flow Deflection Structures

Flow deflection structures extend into the stream channel, and redirect part of the streamflow so that hydraulic forces at the channel boundary are reduced to a non-erosive level. They include a variety of measures that differ somewhat in configuration and function and fall under names such as: groins, dikes, retards, bendway weirs, and Iowa vanes.

Dikes and retards are the most common indirect methods. These are defined as a system of individual structures that protrude into the channel, generally tranverse to the flow. Other terms which are often used are "groins", "jetties", "spurs", "wing dams", and if they protrude only a short distance into the channel, "hard points". The term "dikes" is also used in some regions to refer to earthen flood-containing structures, which elsewhere are called "levees", but that usage is not relevant here.

Because dikes and retards extend into the channel, they are subject to severe attack. Those designs which involve "perishable" materials or mechanical connections are susceptible to gradual deterioration and to damage by debris, fire, ice, and vandals. Therefore, inspection and maintenance is essential.

Channel capacity at high flow is decreased initially. The channel will usually adjust by forming a deeper, though narrower cross-section, and the ultimate effect may even be an increase in capacity. However, the extent of the adjustment cannot be always be predicted reliably, even with physical or numerical models. Since conservative assumptions on future deposition and vegetative growth would be necessary, dikes or retards should be employed with caution on flood-sensitive projects.

Dikes and retards may be a safety hazard if the stream is used for recreation, and the esthetics often leave much to be desired, although vegetative growth lessens the impact in most regions.

Advantages. Little or no bank preparation is involved for indirect protection. This reduces cost and riparian environmental impacts, simplifies the acquisition of rights-of- way, eliminates material disposal problems, and usually allows existing overbank drainage patterns to remain undisturbed. Existing channel alignment and geometry can be modified, although the changes may not always be beneficial or predictable. Indirect approaches usually increase geotechnical bank stability by causing deposition at the bank toe, although this process is not immediate enough or positive enough in all cases.

Indirect methods offer the opportunity for incorporating a wide variety of environmental features. They can be designed to generate scour holes and, thus, they may improve aquatic and terrestrial habitat by increasing diversity, although sometimes at the expense of shallow water habitat. Conversely, they can be designed to trap sediments and create shallow-water areas near the streambank. In arid areas, the reduction of water surface area, thus evaporation, is usually considered a benefit. Many designs use locally available material.

Disadvantages. Where geotechnical bank instability or erosion from overbank drainage is a major factor, the fact that indirect protection does not immediately relieve these problems can be a fatal flaw, requiring the use of bank armoring methods along with geotechnical stabilization measures.

Because significant changes in flow alignment, channel geometry, roughness, and other hydraulic factors often result from indirect protection structures, special attention must be given to the stream's response. Because flow deflection methods extend into the stream channel, construction may be difficult, especially during high flow.

Typical applications. Dikes and retards can be applied to a wide range of conditions. However, the most common use is on shallow, wide streams with moderate to high transport of suspended bed material. Shallow depths reduce the required height of structures, a wide channel provides room for the channel alignment and geometry to adjust, and suspended bed material accelerates the rate of induced deposition.

One of the more common application for deflection structures is to concentrate the low-flow channel in an enlarged or incised channel. Depending on the bed material load of the stream, these structures can accelerate the establishment of psuedo-floodplains within the channel margin while concurrently scouring a deeper channel thalweg that improves habitat during critical low-water periods. When properly constructed, the net effect of these structures on the water surface elevation during flood events can be practically nil.

Where long-term funding is provided, they are often built in increments to reduce costs by modifying the river's form gradually, and taking advantage of subsequent deposition to reduce total cost. Examples are: (1) Building at a low elevation first, then raising the structures after several years of deposition within the original structures, and (2) Using less costly pile structures in deeper water, then permanently capping with stone after deposition has reduced the amount of stone required.

Dikes and retards can be used to stabilize the channel alignment upstream and downstream of armor revetments in bends, since the shallower depths, moderate velocities, and less concentrated drift loads there are more suitable to in-channel structures. They can be used where establishment of riparian vegetation is a high priority.

Other flow deflecting methods include bendway weirs and Iowa vanes. These structures are fully submerged during most or all flows, and affect secondary currents so that there is no longer a net sediment transport away from the toe of the bank. Consequently, a more uniform cross section shape, with shallower thalweg depths and a wider channel at low flow is possible. Counteracting a meandering river's tendency to deposit on point bar faces, accompanied by a strong tendency to scour in the thalweg of bends, whether or not the concave bank was armored, has been one of the most intractable problems of river engineering. These two methods show promise of providing a solution to that problem. However, the benefits ascribed above to these structures may be contrary to the objectives of many stream restoration projects and their utility for such projects may be limited.

An incidental effect of these two techniques might be to increase energy loss in bends at low flow, through both the modification of channel shape and the roughness introduced by the structures themselves. This would be beneficial on many streams, especially channelized ones that have suffered a lowering of low flowlines, with detrimental effects on aquatic habitat, riverside facilities, and the water table. A bend would in effect act as a very long grade control structure, without interfering with the natural flow of the stream, or if the structures are submerged below navigation depth, without interfering with navigation.

"Bendway weirs" were developed by the U.S. Army Corps of Engineers (USACE) to improve navigation flowlines, increase channel width in bends to improve navigation and decrease maintenance dredging requirements. The weirs are level-crested stone structures angled upstream, with a crest elevation about 15 feet below low water. The design is based on USACE physical model studies at the Waterways Experiment Station (WES). The first system was installed in 1990 on the Middle Mississippi River upstream of the mouth of the Ohio River.

A number of similar structures have been used on smaller streams throughout the US in recent years and have also been dubbed “bendway weirs”. While these are also generally low-profile deflection structures, the majority do not function in the same manner as the original bendway weir and are probably better characterized as “upstream-angled groins”.

Iowa vanes are a patented technique marketed by River Engineering International, Inc., Iowa City, Iowa. The structures are a foil-like device that function by dissipating or moving the secondary currents in a bendway. They were first used in 1985 on the East Nishnabotna River near Red Oak, Iowa. The general method has the potential for being a powerful tool, as more experience is acquired to define limiting conditions for effectiveness and to optimize potential applications for use with other techniques in severe conditions. The layout with respect to flow alignment appears to be critical to success.

The principal design considerations for flow deflection structures are the structure length, height, orientation (angle to the bank), spacing and the type of material used for its construction. Unfortunately, little guidance is available for most of these parameters.

Material type is probably the most straight-forward issue. In general, these structures are nearly always constructed of graded riprap. Because the design tolerances of riprap are better known than for any other material, it is the safest to use. The ability of stone to “launch” into a scour hole and provide a measure of self-protection, deflection structures built of riprap are much less susceptible to failure than deflectors built of logs, gabions, or other materials. On systems with a very high sediment load, permeable timber deflectors have been used successfully to initiate sediment deposition and create bars. Timber deflectors are very susceptible to damage from ice and debris, however, and structures constructed of these materials are not generally recommended.

The optimum height of flow deflection structures depends on the objectives of the project, the nature of the erosion at the site and the general channel geometry. Structures intended to generate a low-flow channel, disrupt secondary currents, protect against toe erosion, or placed along a straight reach generally need not be placed high above the bed of the stream. Many designers try to match the relative elevations of natural point bar features under these circumstances. On tight bends, or where the erosion occurs along the entire bank face, the structures generally need to be higher. They are commonly constructed with a top that slopes from nearly the top of the bank to only a fraction of the flow depth (about 20 percent) at the toe. In cases where impacts to the water surface elevation during flood flows is a concern, a balance between the structure length and height must be sought. Sand and gravel-bed streams that scour and adjust to the placement of deflectors can generally accommodate a flow blockage of only about 15 percent without experiencing impacts to the water surface profile.

Structure length is almost always determined with the objective of providing a desirable flowline for the thalweg and bank. When the structures are intended to trap sediments and promote the development of bars, natural bars on the stream can be used as a guide to help determine the necessary structure length. Structure lengths exceeding 30 percent of the channel width generally require more detailed analyses.

Spacing of deflection structures (groins, barbs, hardpoints) is generally based on the length of the structure and the width of the channel. This is one of the few parameters for which acceptable design guidelines exist. Table 7.5 presents guidelines found in the literature.

Table 7.5 Recommended groin spacing (S) as a function of groin length (L) and stream width (B).

Author	Spacing S/L	Spacing S/B	Type of Bank	Remarks
United Nations(1953)	1		Concave	General practice
	2-2.5		Convex	General practice
Ahmad (1951)	4.29		Straight	
	<2.5		Curves	
Joglekar (1971)	2~2.5			Upstream groins
US Army (1984a)	2			Mississippi River
Mathes (1956)	1.5			
Strom (1962)	3-5			
Acheson (1968)	3-4			Varies depending on curvature
Altunin (1962)	4		Straight	$\alpha > 75°$
	3			for $0.005 \leq I \leq 0.01$
	2			for $I > 0.01$
Richardson et al. (1975)	2- 6			For bank protection
	3-4			T- head groins for navigation
	1.5-2			Deep channel for navigation
Mamak (1956)	2-3	1		
Macura (1966)		0.5	Concave	
		5/4	Convex	
		3/4-1	Straight	
Jansen et al. (1979)		1-2		In constricted rivers
		0.5-1		
Blench et al. (1976)	3.5			
Copeland (1983)	> 3		Concave	
Akantisz et al. (1989)		0.9-1		For $\phi = 45°\text{-}50°$ R/B = 8- 13.5
				For $\phi = 55°$ R/B = 8
				For $\phi = 55°$ R/B = 13.5
Kovacs et al. (1976)	1-2			Danube River
Mohan and Agraval	5			Submerged groins of height
Maza Alvarez (1989)	5.1- 6.3		Straight	sloping-crested groins for bank
	2.5- 4		Curves	protection

The most contentious issue with respect to flow deflection structures these days seems to be the appropriate orientation. Some argue that the only effective orientation is upstream (and they may even identify a specific angle), while others point out that for every upstream-angled structure, a dozen have been constructed perpendicular to the flow or angled downstream and have worked effectively for decades. Simply put, this is an intractable issue at this point. Additional research is needed to define the limits of application and to formulate the appropriate guidance.

Boulder Clusters

Boulder clusters are groups of large rocks (>10 in. diameter) placed in a stream to improve habitat. Flow separation around the boulders leads to the formation of eddies or vortices (a swirling mass of water) in their wake. These vortices diffuse sunlight and create overhead cover for fish. They also generate scour that develops pockets of deeper water and associated coarse substrate that add to the physical diversity of a stream reach.

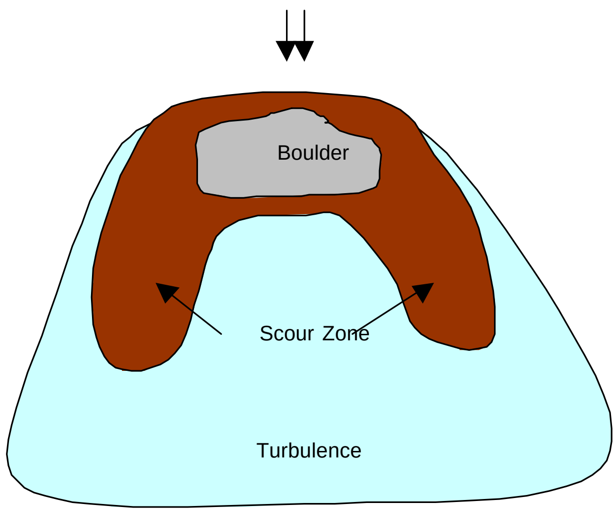


Figure 7.2 Scour around a boulder.

Boulders, and the turbulence and scour they create, are among the types of habitat used by both juvenile and adult fish. Preferred summer microhabitat for many juvenile fish consists of deep water in conjunction with submerged cover. This cover is used to elude predators. Adult fish also use the scour pools for resting and hiding and many spawning adults appear to select spawning sites on the basis of the closeness of cover.

Boulder clusters can be prescribed for sections of stream reaches that have; a) a dominance of riffle over pool, and b) riffles comprised of coarse gravel to cobble substrate, with few boulders and other associated cover. Alternatives should emphasize multiple boulder groupings in conjunction with other designs, such as wing deflectors and bank cover, to ensure stability of the thalweg and optimize benefits. Additional considerations for the selection of potential boulder sites are listed below:

1. Use boulders only where cover and/or diversity is limited.
2. Use fewest boulders possible to attain desired habitat.
3. Boulders should occupy <10% of flow area at bankfull flow.
4. Avoid pools and slow runs. Velocity should exceed 4fps at bankfull.
5. Not recommended for use in sand bed streams.
6. Avoid placement in braided, unstable sections.
7. Use boulders sized for stability at bankfull flow.
8. Avoid placement boulder groupings near the upper end of riffles.
9. Allow sufficient (e.g., 5 m) riffle leading into structures to maximize insect drift.
10. Concentrate boulders in or near channel thalweg to ensure habitat availability during low flow.

The primary design considerations for boulder clusters are a) the number, configuration and location of the structures, and b) the size of the boulders needed for stability. The hydraulic impacts of the boulders should also be ascertained when habitat benefits must be quantified or the potential exists for adverse impacts due to increased velocities or water surface elevations.

Three to five boulders in a triangular configuration in staggered groups or clusters along the riffle or very shallow run appear to be most effective because each group guides turbulent "overhead cover" into a downstream group. To maximize turbulence and scour, boulders should be well-spaced (about 1 diameter between boulders). Boulders placed in the wake of an upstream boulder have minimal benefits, so successive downstream boulders should be placed at the periphery of the wake of upstream boulders. Armoring of banks may be necessary if boulders are placed within a few feet of the banks.

A boulder immersed in flowing water is subject to the hydrostatic surface force of pressure, the body forces of weight (F_W) and buoyancy (F_B), the additional hydrodynamic forces of pressure (normal to the body surface) and viscous shear forces (tangential to the body surface). The normal and tangential hydrodynamic forces can be resolved into the drag force (F_D), and the lift force (F_L). If the immersed body is resting upon the streambed, there is a friction force (F_R) that acts opposite to the direction of flow. A boulder will remain at rest as long as the active forces of drag, lift, and buoyancy are less than the resistive forces of weight and friction.

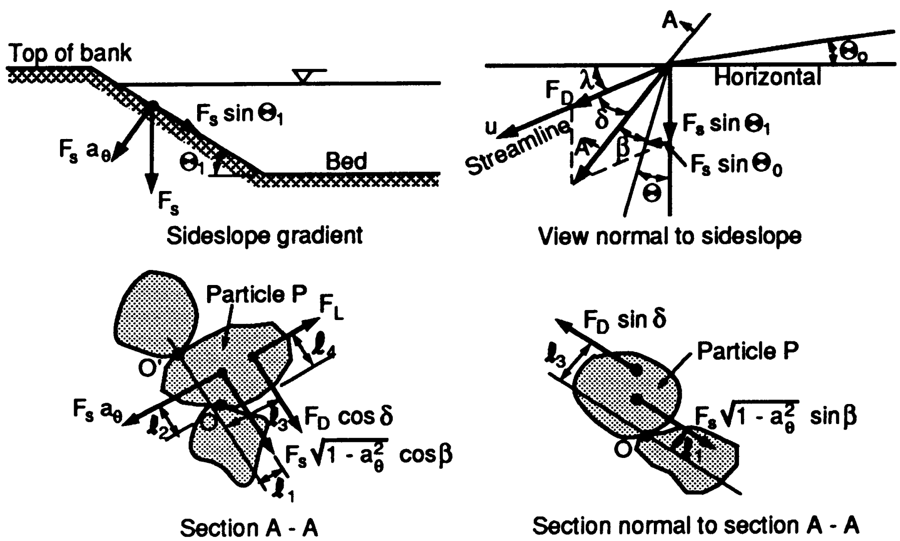


Figure 7.3 Forces acting on a boulder or submerged particle.

Because both drag and lift are functions of the approach velocity raised to the second power, velocity or shear stress is sometimes used as a surrogate for stability analyses. Values of critical velocity and shear stress for boulders, cobbles, and coarse gravels are provided in Table 7.6. For fully turbulent flow over a rough horizontal surface with the boulder fully immersed, incipient motion occurs when:

$$d_s = \frac{(18\ y\ S_f)}{(G-1)}$$

where
ds = minimum boulder diameter (ft)
y = flow depth at bankfull (ft)
Sf = friction slope
G = specific gravity of boulder (typically 2.65)

Table 7.6 Threshold Conditions for sediments

Class name	d_s (in)	f (deg)	t_{*c}	t_c (lb/sf)	V_c (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	25
Large	>40	42	0.054	18.7	19
Medium	>20	42	0.054	9.3	14
Small	>10	42	0.054	4.7	10
Cobble					
Large	>5	42	0.054	2.3	7
Small	>2.5	41	0.052	1.1	5
Gravel					
Very coarse	>1.25	40	0.050	0.54	3
Coarse	>0.63	38	0.047	0.25	2.5

Table 7.6 and the above equation can be useful for a preliminary analysis to ascertain the approximate dimensions of a stable boulder for the project site. However, more detailed analyses are generally warranted. The most universally applicable approach is a moment stability analysis. In a moment stability analysis, a single boulder is evaluated based on the ratio of moments resisting overturning to moments promoting overturning of the particle about the point of contact of the rock with an adjacent boulder or the bed of the stream.

The ratio of moments that resist overturning of the particle, M_R to moments that promote overturning, M_P defines a safety factor, $SF = \sum M_R / \sum M_P$, that provides an index of particle stability. Ratios larger than unity indicate a stable riprap particle; ratios less than unity indicate an unstable particle; and ratios equal to unity indicate a neutrally stable particle. The moment stability analysis procedure presented herein is for the general case, allowing for the analysis of boulders placed on side slopes and including streamlines not parallel to the channel (i.e. accounting for secondary currents).

Plant Materials

Almost all of the plants used in bioengineering can be considered wetland plants, either obligative or facultative. Some of the exceptions would occur in the terrace zone that is infrequently flooded; however, all must be somewhat flood-tolerant. Both herbaceous and woody plants are used. Herbaceous plants may be emergent aquatic plants like rushes and sedges or grasses and other forbs that require non-aquatic, but moist conditions at least part of the year. The herbaceous plants are usually acquired as vegetative material such as sprigs, rhizomes, and tubers. Sometimes seed is acquired, but is used when the threat of flooding is low in the bank and terrace zones. Otherwise, they would wash out quite easily unless they are seeded underneath or in a geotextile mat or fabric that is securely anchored.

Woody plants used for bioengineering purposes usually consist of stem cuttings, those that quickly sprout roots and stems from the parent stem. These are plants such as willow, some dogwood, and some alder. They can be supplemented by bare-root or containerized stock, particularly in the bank or terrace zones where they are not subjected to frequent flooding. Gray and Sotir (1997) list several such plants that can be used in bioengineering and relate their flood tolerances, along with some other characteristics.

There are three suitable methods to acquire plants for bioengineering treatments: a) purchase plants, b) collect plants from the wild; and c) propagate and grow plants. Each has noteworthy advantages, but also critical disadvantages that make plant acquisition and handling an important and complex process. Table 7.7 presents these advantages and disadvantages. Regardless of the method chosen, it is necessary to conduct the following steps (Pierce, 1994):

a. Determine the available hydrologic regime and soil types. General positioning of the plant type, e.g., emergent aquatic, shrubby willow, should be in accordance with the plant zone (splash, bank, and terrace).

b. Prepare a list of common wetland plant species in the region and more preferably, in the watershed containing the stream of concern, and match those to the hydrology and substrate of the target streambank reach to be addressed.

c. Select species that will match the energy of the environment and the hydraulic conveyance constraints that may be imposed by the situation. For instance, one must be careful to use low-lying and flexible vegetation that lays down with water flows if hydraulic conveyance must be maximized. In such cases, use flood-tolerant grasses or grass-like plants and shrubby woody species.

d. Select species that will not be dug out or severely grazed by animals, especially muskrat (*Ondatia zibethieus*), nutria (*Myocastor coypes*), beaver, Canada geese, and carp (*Cyprinus carpio*). Other animals may influence plant growth and survival. If plants chosen are unavoidably vulnerable to animal damage, then plant protection measures must be used, such as fencing, wire or nylon cages around them, or use of repellents.

e. Determine additional special requirements and constraints of the site. For instance, some sites may be prone to sediment deposition or have a bank geometry that is almost vertical. In such cases, it may be difficult to obtain success with emergent aquatic plants that may become covered with sediment and suffocate or which have too deep of water in which to grow unless the bank is reshaped. The former situation may necessitate the use of willow that can be planted as cuttings or posts and be less susceptible to complete coverage by sediment.

f. Prepare a suite of species that would be suitable. This may be limited to those currently available from commercial sources if there is no possibility to collect in the wild or have plants contract grown.

Purchasing Plants

Prior to the purchase of any plant materials, you should acquire a list of wetland plant suppliers, such as "Directory of Plant Vendors," (USDA Soil Conservation Service, 1992). Request vendors' catalogs and plant availability lists. Determine in what condition the plants from each supplier are delivered, potted, bare root, rhizomes and tubers, or seed. This is important because if the plants are to be used in the splash zone where they may be partially covered with water, seed of emergent aquatic plants will not germinate under water. Match the plant list against species availability, and do not assume that all species advertised will be available in needed quantities. Order samples, if available, and verify plant condition and identification. Negotiate a flexible delivery schedule allowing for unpredicted delays in planting. Some suppliers may grow plants on contract but it will be necessary to contact them several months to a year before the plants are needed.

Collecting Plants from the Wild

Collecting plants from the wild may be very demanding because of "hard-to-reach" plants that are off main access routes. Wild plants must then be moved immediately to a nursery or hold-over site or to the project site. Logistical and plant handling problems need to be carefully assessed and solutions planned well ahead of time. Care should be taken if this method is selected because of the possibility of contaminating the harvested donor plants with unwanted weedy species that could become a problem at the project site. Samples should be collected ahead of time in order to determine what kind of problems will be encountered in collecting, transporting, and storing each species. Caution should be exercised in collecting plants from harvesting areas so that the plant community is not extirpated, left functional, and the ecosystem not damaged. This can be done by not harvesting in one spot, but dispersing the harvest areas. Care should be taken by harvesting only fairly common plants. Certainly, rare plants should be avoided.

Growing Plants

Plants to be grown for planting can be grown in a greenhouse or other enclosed facility or in the case of emergent aquatics, outdoor ponds or troughs containing water. In either case, the plants must first be acquired from the wild or other growers, and propagated. If seeds are used for propagation, they must first be stratified (subjected to various treatments such as soaking and temperature differences), but germination requirements for most wetland plant seeds are unknown. If a greenhouse is to be used, a number of limitations and constraints must be overcome, such as room for pots, adequate ventilation, and requirements or problems associated with fertilizing, watering, and disease and pest control. Plants can be grown in coir carpets, mats, or rolls, to facilitate early establishment, ease of transport, and rapid development. Emergent aquatic plants, especially, may be hydroponically grown in the greenhouse or in outside troughs. Then, they can be transported to the planting site ready to grow with roots already established in the carpet, mat, or roll.

Table 7.7 Considerations for plant material acquisition

Method	Advantages	Disadvantages
Purchase	Plants are readily available at the planting location in predicted quantities and at the required time. No special expertise is required to collect or grow the plants. No wild source for the plants must be found and there are no harvesting permits to obtain from state or local governments. Cost can be more readily predicted and controllable than harvesting from the wild or growing your own.	Plants may arrive in poor condition. Selection of species is limited. Plants may not be adapted to the local environment. Cost may be high and shipping cost needs to be considered. Quantities may be limited. It may be necessary to store large quantities of plants and procure adequate and appropriate storage facilities.
Collect From Wild	Plants are likely to be ecotypically adapted to the local environment. Plants can often be collected at a low cost. Plants can be collected as needed and will not require extended storage. Availability of species is very flexible and can be adjusted. No special expertise is required to grow the plants. A very wide diversity of plants is available.	Weedy species may be inadvertently transplanted to the project site. A suitable area or areas must be located. Plants may be stressed, diseased, or insect infested and not in an appropriate condition for planting. Rare plants or weeds may be harvested by mistake. Cost of collection and logistics may be very high. Outdoor hazards such as snakes, adverse weather, noxious plants, and parasites may interfere with collection efforts. It is often necessary to procure a permit for collecting native plants.
Grow	All of the advantages of purchasing plants can be realized. The variety of species available can be as diverse as for plants collected in the wild and plants can be planted in large quantities. Plants can be available earlier in the season than purchased or collected plants. Low cost is one of the primary reasons to grow stock for planting.	Space and facilities must be dedicated to growing plants. Personnel with time and expertise to grow the plants may not be available. There is an up-front investment in both fixed and variable overhead items in order to establish a growing facility and it may not be justified unless there is a large and continuing need for planting stock.

Handling of Plant Materials

Plants need to be handled carefully to ensure their survival between the phases of acquisition (purchasing, growing, or harvesting from the wild) and transplanting because they will undergo transportation and planting shock. Many problems associated with poor plant survival occur from the handling of the plants between the nursery or collection site and the project planting site. Generally, the plant material needs to be kept cool, moist, and shaded (Hoag, 1994). They must be treated as living material; if the living attributes are lost, then the project is much more prone to fail even though dead plant materials in a bioengineering treatment can offer some erosion control through their physical attributes, e.g., acting as bank armor, runoff retention through checkdam effects, current and wave deflectors. Plants are most easily collected when dormant. When plants are dormant, there is substantially more forgiveness in how they are handled.

Design criteria for bioengineering treatments are generally lacking. Work is underway to develop specific guidance, and initial results of this effort are presented herein. Guidance for geotextile coir rolls, for example, has recently been developed by the authors and was presented in a previous section in more detail than are some other techniques in this section. As guidance for other techniques is formulated, the authors will present summary reports available from the internet at *http://www.wes.army.mil.*

Woody Plants

Woody plants, particularly cuttings, should be collected when dormant; their survival decreases a lot if they are harvested and planted in a non-dormant state. With bareroot or unrooted cuttings, keep them cool, moist, and in the dark until they are ready to be planted (Hoag, 1994b). They can be stored in a large cooler at 24-32 deg F until just before planting. Cuttings can be stored in this manner for several months (Platts et al. 1987). The cuttings can be kept in a cooler, root cellar, garage, shop floor, or any place that is dark, moist, and cool at all times (Hoag, 1994b). Often, cuttings are placed on burlap and covered with sawdust or peat moss and then covered with burlap after being moistened.

Hoag (1994b) advocates soaking of cuttings for a minimum of 24 hours, whether they are coming out of storage or directly after harvesting in the late winter to early spring (Hoag et al. 1991a; Hoag et al. 1991b; Hoag 1992). Some research recommends soaking the cuttings for as much as 10-14 days (Briggs and Munda 1992; Fenchel et al. 1988). The main criteria is that the cuttings need to be removed from the water prior to root emergence from the bark. This normally takes 7 to 9 days (Peterson and Phipps 1976). Soaking is important because it initiates the root growth process within the inner layer of bark in willows and poplars (Hoag, 1994b).

When woody plants are moved from the nursery, holding, or harvesting area, to the project site, they should continue to receive careful handling by keeping them moist and free from wind desiccation. The latter can be achieved by ensuring they are covered with a light-colored (to reflect heat) and moist tarp. In the case of cuttings, they can be moved to the project site by moving them in barrels with water in them or some similar method. Actual planting of the plants should follow the digging of holes as soon as possible, preferably no longer than 2-3 minutes, so that the excavated soil does not dry out. Use only the moist, excavated soil for backfill of the planting hole. Backfill should be tamped firmly to eliminate all voids and to obtain close contact between the root systems and the native soils. When using containerized or balled and burlap stock, excess soil should be smoother and firmed around the plants leaving a slight depression to collect rainfall. Plants should be placed 1 to 2 inches lower than they were grown in the nursery to provide a soil cover over the root system (Leiser, 1994).

Live Stakes and Posts

Cuttings (live stakes) should be prepared from woody plants that root adventitiously (e.g. Salix spp.), obtained from as near the site as possible and should be free from obvious signs of canker diseases. Cuttings should be dormant. The diameter of cuttings should be not less than 3/8 inch, and larger cuttings are generally preferable. The length of cuttings should be a minimum of 12 in, but no shorter than is necessary to reach adequate moisture in the soil. Figure 7.3 is a schematic of live stakes.

Cuttings should be cut to size in any expedient manner, but should not result in frayed ends or bark. During preparation, the orientation of cuttings should be maintained, i.e. all cuttings should be arranged basipetally (tops up, bases down). Cuttings should be tied in bundles sized for handling, and the cut tops painted with a water base paint, e. g. interior latex paint, to seal the cuts and identify the tops. Alternatively, the bases may be cut at an angle to facilitate driving as well as identify the ends.

Cuttings should be prepared no longer than one week before planting unless they are to be placed in cold storage. Cuttings should be maintained in moist conditions at all times. They may be stored out-of-doors in shade and submerged in water, either in natural streams or ponds or in containers. When stored in containers, the water should be changed daily. They may be stored, wrapped in wet burlap or plastic, under refrigeration at 32-45 F. During planting, the cuttings should be kept moist until planted. This may be accomplished by carrying in planting bags or buckets, covered with moist vermiculite, sawdust, or similar material, or in water.

Cuttings may be pushed into ground that is soft. In hard ground where this is not possible, cuttings should be planted with dibbles, star drills or other devices to avoid damaging the bark of the cuttings. Cuttings should not be driven with hard hammers, but soft-blow hammers are acceptable. Cuttings should be planted to within 2 - 6 inches of the tops, or should be cut leaving no more than 6 inches exposed. The soil should be tamped firmly around the cuttings to provide a firm hold, and no air pockets or voids should remain around the cuttings.

Fascines or Wattles

Wattling bundles should be prepared from live, shrubby material, from species which will root, such as Salix app. (willow), etc. Wattling bundles may vary in length, depending on materials available. Bundles should taper at the ends and should be 1 to 1 1/2 feet longer than the average length of stems to achieve this taper. Butts should be no more than approximately 1 1/2 inches in diameter. When compressed firmly and tied, each bundle should have an 8 - 12 in diameter.

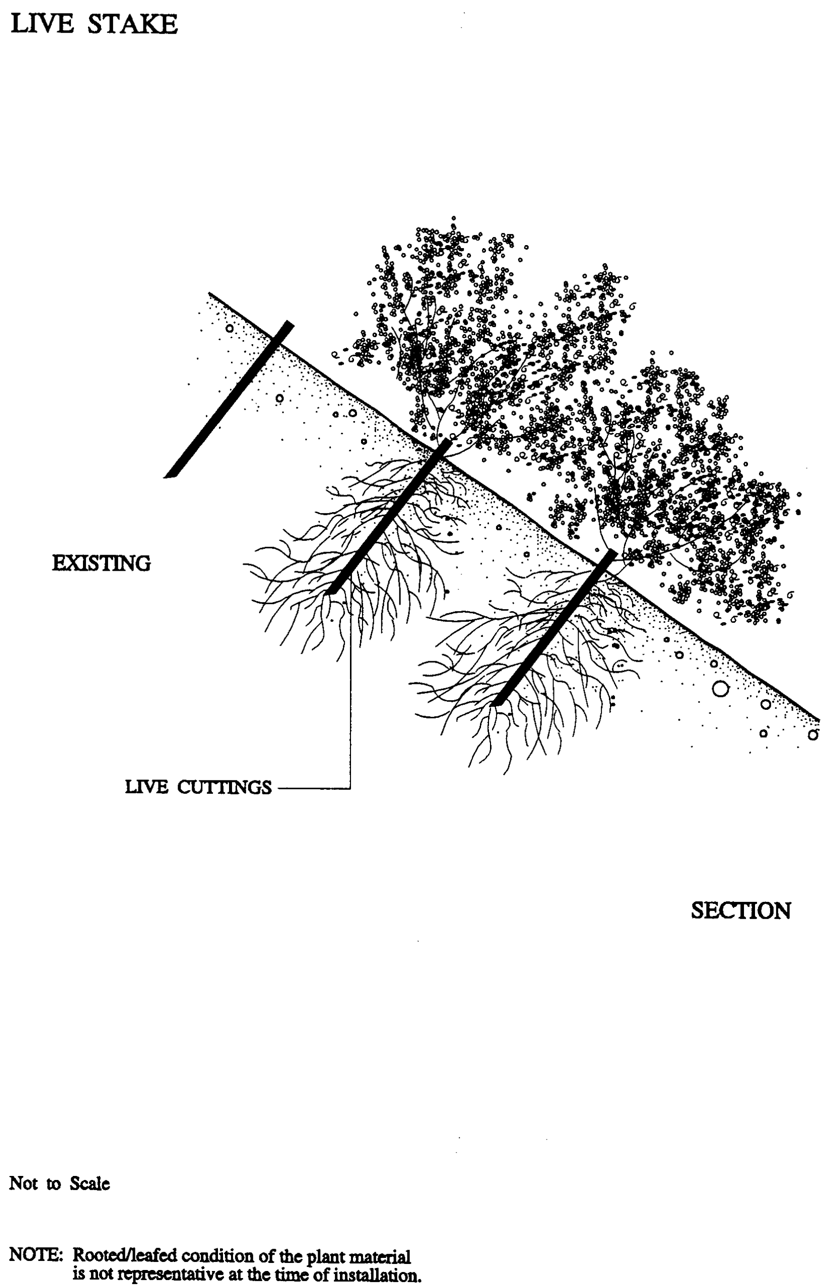


Figure 7.3 Live stakes (figure from Robbin B. Sotir and Assoc.).

Stems should be placed alternately (randomly) ln each bundle so that approximately one-half the butt ends are at each end of the bundle. Bundles should be tied on not more than 15 inch centers with a minimum of two wraps of binder twine or heavier tying materials with a non-slipping knot. Tying may be done with strapping machines as long as the bundles are compressed tightly. Figure 7.4 is a schematic of a wattle.

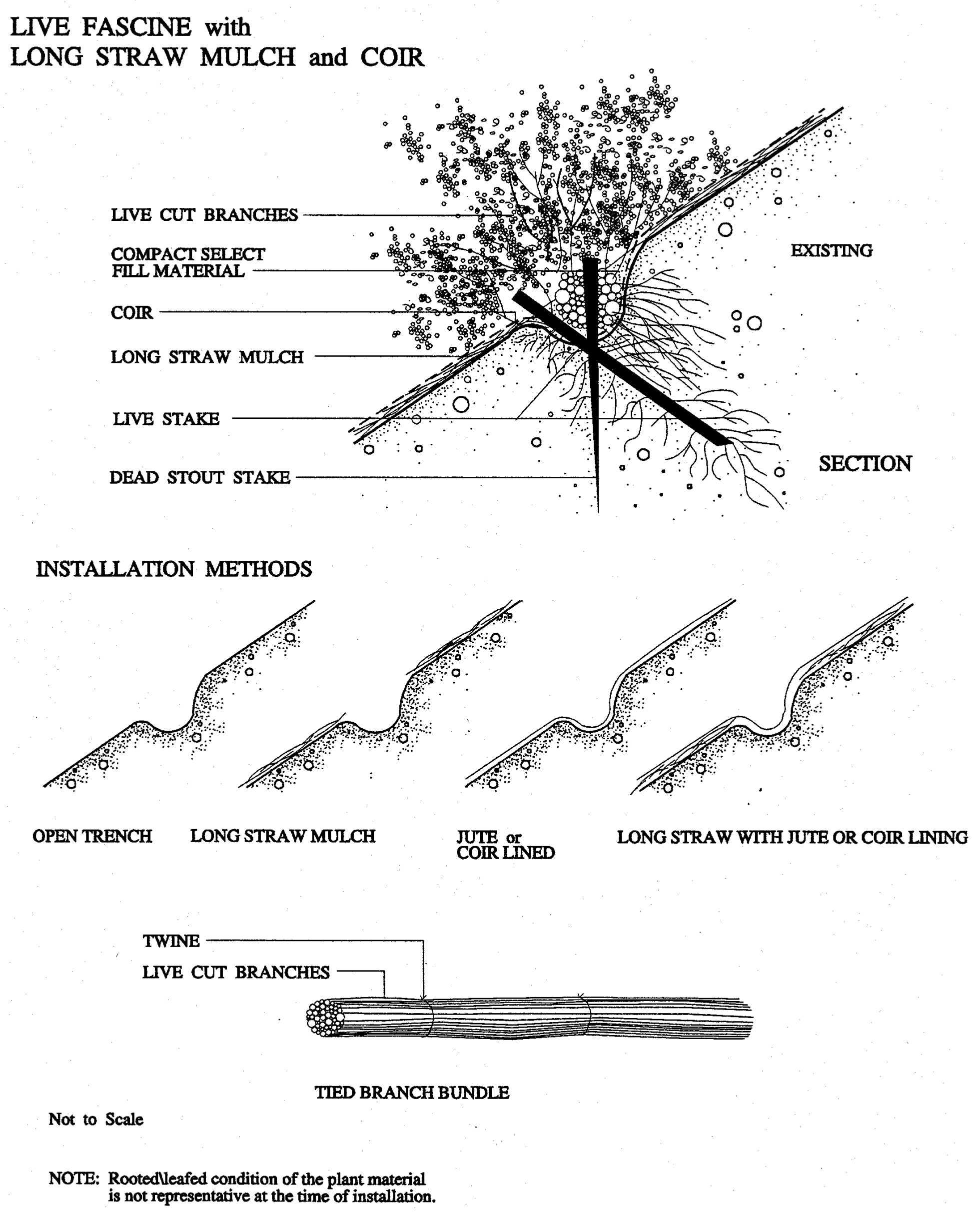


Figure 7.4 Wattle schematic (figure from Robbin B. Sotir and Assoc.)

Bundles should be prepared not more than two days in advance of placement when kept covered and in the shade. If provisions are made for storing in water or sprinkled as often as needed to be kept constantly moist , covered, and in the shade, they may be prepared up to seven days in advance of placement.

Bundles should be laid in trenches dug to approximately one-half the diameter of the bundles. Bundles should be placed with ends overlapping at least 12 inches. The overlap must be sufficient to allow the last tie on each bundle to overlap. Wattling should be covered immediately and seeped. Workmen are encouraged to walk on the wattling as work progresses to further work the soil into the bundles. Ten to twenty percent of the bundle should be left exposed when all construction is completed. This allows better rooting and helps intercept water and detritus.

Bundles should be staked firmly in place with vertical stakes on the downhill side of the wattling not more than 24 inches on center and with stakes through the bundles at not more then 36 inches on center. When bundles overlap between two previously set guide or bottom stakes, an additional bottom stake should be used at the midpoint of the overlap. The overlap should be "tied" with a stake through the ends of both bundles and inside the end tie of each bundle. Stakes may be made of live willow stems greater than 1 1/2 inches in diameter or they may be construction stakes (2 x 4 x 24 to 2 x 4 x 36, cut diagonally) or a mixture of the two. Reinforcing bar may be substituted, but is not generally recommended unless wood stakes cannot be driven into the soil. All stakes should be driven to a firm hold and a minimum of 18 inches deep. Where soils are soft and 24 inch stakes are not solid (i.e., lf they can be moved by hand), 36 inch stakes should be used. Where soils are so compacted that 24 inch stakes cannot be driven 18 inches deep, 3/8 -or 1/2-inch reinforcing bar should be used for staking. When rebar is used, the tops should be bent over to hold the wattling in place.

Work should progress from the bottom of the slope to the top and each row should be covered with soil and packed firmly behind and into the bundle by tamping or walking on the bundles or by both these methods. Exposure of the wattling to sun and wind should be minimized throughout the operation. Trenches should be dug only as rapidly as the wattling is being placed and covered to minimize drying of the soil in the trench and of the backfill.

Branch Packing or Brush Layering

Live but dormant brush of willow species should be used. When there is a shortage of willow, up to 50% of the brush may be of non-rooting species. When non-rooting species are used they should be mixed randomly with the rooting species.
Length of brush should vary according to the particular installation and should be specified on the plans. The length may vary from 2 - 8 feet or more. Hand trenched brush layering used for small gully repair should be from 2-3 feet long. Hand trenching should start at the bottom of the slope. Trenches should be dug 24 - 36 inches into the slope, on contour, and with a downward slope of 10 - 20 deg.

Brush should be placed with butts inward into the slope with 6 - 12 inches of the tips extending beyond the fill face. Brush should be arranged randomly, perpendicular and at angles of up to 30 deg. from the perpendicular to the slope face, i.e. in a criss-crossed manner. Brush should be 3 - 4 inches thick in hand trenched placement work and 5 - 6 inches thick in fill work. Thickness should be measured after compression by the fill or covering soil.

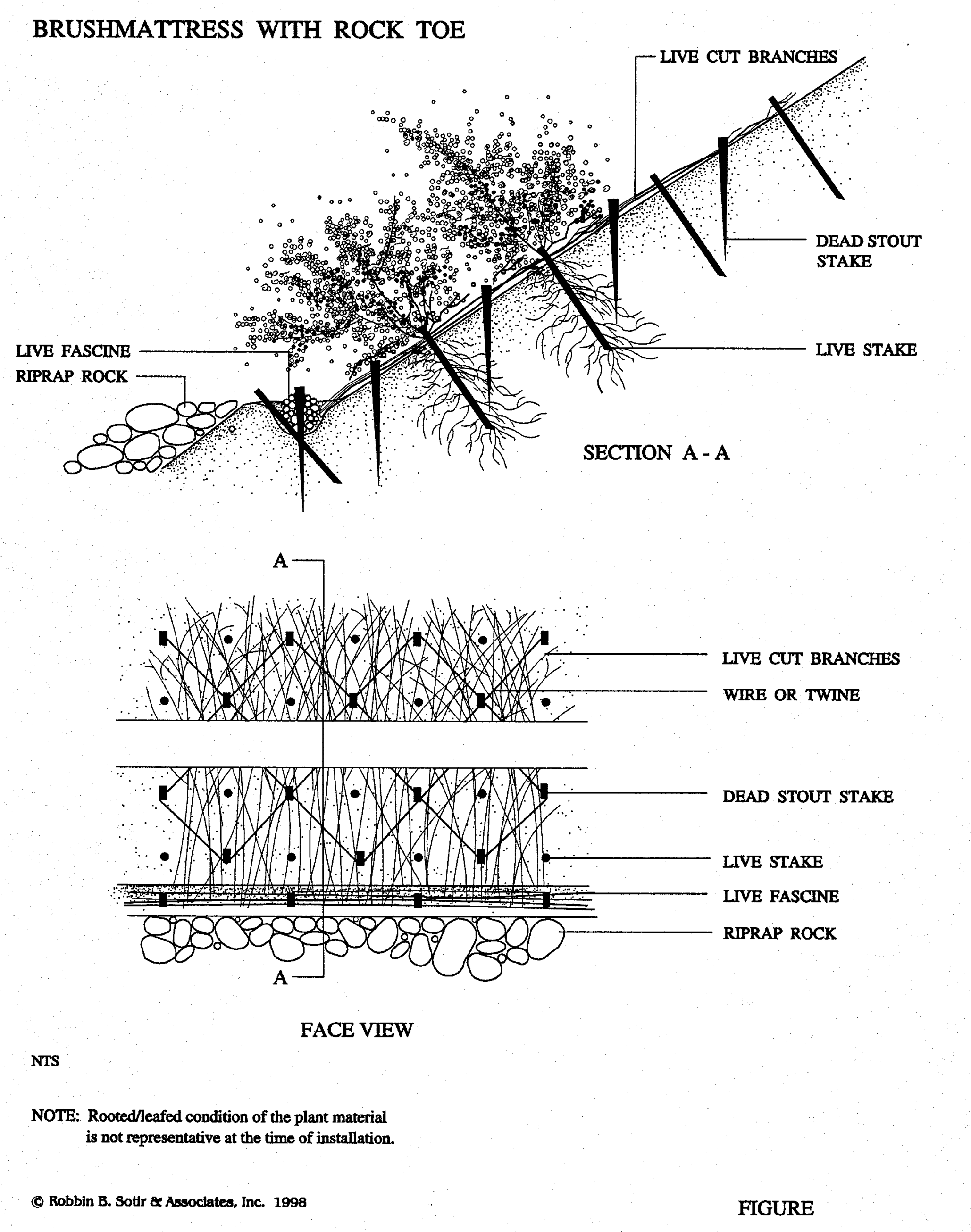


Figure 7.5 Brush mattress (figure from Robbin B. Sotir & Assoc.).

Brush layers should be placed on successive lifts of well covered fill. Each layer should be covered with soil immediately following placement and the soil compacted to 90 percent of maximum. Covering may be done by hand or with machinery. Interplantlng of woody plants (transplants and/or unrooted willow cuttings) and grasses should follow placement of the brush layering as specified for the site.

Container-Grown Plants

Containers should have a minimum size of 9 cubic inches in volume and depth of 8 inches. The growing medium should be any medium that will produce good quality plants. The plants specified usually grow best in a well-drained, well aerated medium. The growing medium should be well filled with roots so that roots and the medium form a cohesive unit when removed from the container. Roots should be in good condition and actively growing with white tips. Top growth should be commensurate with root growth, free from dead wood or foliar diseases, and be a minimum of 5 inches high. Shrub species should be pruned during production if necessary to stimulate branching and avoid 'logginess', i.e. bare lower stems and inability to stand upright.

Containerized plants should be healthy, shapely, and well rooted, with roots showing no evidence of having been damaged, restricted, or deformed. Soil mass in the container should be sufficiently filled with roots so that it will maintain its integrity when removed from container. Plants should be free of disease, insect pests, eggs or larvae and should be subject to inspection and approval at the place of growth and/or upon delivery. Plant stems should be turgid. Branch structure should be similar to naturally occurring plants of that species. Root to shoot ratio should be approximately 1:1. Plants should be acclimated to the planting site, or "hardened off" prior to planting.

Planting on slopes should proceed from the top to the bottom of the slope except that installation of wattling and brush layering should proceed from the bottom to the top. Plantings should be randomly staggered to avoid straight rows. Planting patterns and densities may vary within sites to avoid unfavorable sites conditions such as rock outcroppings, existing vegetation end engineering structures. Pits for trees and shrubs should be excavated to a minimum of 1 1/2 times the size of the container. The side of the pit should be vertical, lightly scarified, and the bottom should be loosened to a minimum additional depth of 6 inches.

The planting should take place no longer than two to three minutes following digging, and the plants should be removed from containers just prior to planting. Containers should be cut on at least 2 sides and removed without damage to the root ball. The roots should be teased away from the root ball with fingers. Set plant upright and in the center of pit. Adjust plant by mounding native soil in bottom of pit so that root ball will be at finish grade as shown on the drawings. Fertilizer, when required, should be placed with at least two inches of soil cover and no closer than two inches to the root ball. Plants should set one to two inches lower than they were grown in the nursery to provide a soil cover over the root system. Only the moist soil excavated for the backfill should be used. Backfill should be tamped firmly to eliminate all voids and to obtain intimate contact between the root systems and the native soils. Excess soil should be smoothed and firmed around the plants leaving a slight depression to collect rainfall.

All plants should be thoroughly watered on the same day of planting. Water used in installation of plantings should be clean, clear and free from injurious amounts of oil, salt, acid, alkali or any other toxic substance. No plants should be distributed or cans cut than can be planted and watered on that day. Plants that have settled should be reset to proper grade.

Herbaceous Plants

Plant handling requirements of herbaceous plants are even more rigorous than woody plants as a general rule because they are usually obtained in the spring when nurseries have them ready to ship or when they are readily identified in the wild for collection. At those times, they are very susceptible to desiccation mortality. Consequently, they must be kept in a moist, shaded condition, or even better, in water-filled containers from the time of collection from the wild or receipt from the nursery to the time of transplanting. If herbaceous plants are identified and tagged for collection in the spring or summer, they can be collected when dormant in the late fall or winter. During those times, they can be handled more freely, but should still be prevented from drying out. When transporting from the nursery, holding, or harvesting area to the project site, this should be in a covered vehicle. If the weather is very hot, cooling from ice or refrigeration may be necessary. Exposure to high winds should be avoided. Plants can be placed in a water-filled ditch and covered with soil in a shaded area for storage of several days while awaiting planting. It is best not to store plants longer than necessary, and delivery should be scheduled to match planting dates.

If herbaceous plants are to be grown, they will need to be grown from seed or from collected rhizomes, tubers, or rooted stems or rootstock from the wild. Most wetland plant seed needs to be stratified and will not germinate under water even after stratification. An experienced wetlands nursery person should be consulted before attempting to grow wetland plants from seed. Often, a cold treatment under water is necessary for stratification (Pierce, 1994). There are various other stratification methods of wetland plants, such as hot and cold temperature treatments and treatments with various fertilizers. Rhizomes, tubers, and rooted stems and rootstock of wetland herbaceous plants can be grown out in wet troughs or ditches and ponds containing fertilized sand and peat moss. Only enough water is necessary to keep the rhizomes, tubers, etc. from drying out. Plants can be grown out in the greenhouse over colder months, but will require hardening before transfer to the project site.

Hoag (1994b) stated that hardening off can be accomplished by removing the plants from the greenhouse and placing them in a cool, partially shaded area for 1-2 weeks. This is generally a lathe or slat house. Some are constructed with snow fencing which has wooden slats woven together with wire. According to Hoag (1994b), this type of structure allows a small amount of direct sunlight and solar radiation through the slats to the plants, but not enough to burn them. A partially shaded spot near the planting site will also work. It is important to keep the plants well watered and misted during the hardening off period. Plants should continue to receive regular irrigation when moved from the nursery to the project site. All plants should be watered immediately before planting (i.e., the same day) so that moisture in the containers is at or near field capacity. Handling during planting should be such that overheating or excessive drying is avoided.

GRASS SEEDING

All seed should be delivered to the site tagged and labeled. Seed should have a minimum pure live seed content of 80 percent (percent purity X percent germination) and weed seed shell not exceed 0.5 percent.

Fertilizer should be ammonium-phosphate-sulfate and should be delivered in unbroken and unopened containers, labeled in accordance with applicable state regulations, and bearing the warranty of the producer for the grade furnished. Fertilizer should be uniform in composition, dry and free flowing, granular, or pelleted.

Straw should be new, derived from cereal grains and free from mold and noxious weed acid. Strew should be furnished in air-dried bales. Wood fiber should be wood cellulose fiber that contains no germination or growth-inhibiting factors. It should be produced from non-recycled wood such as wood chips or similar material and should have the property of even dispersion and suspension when agitated in water. It should be colored with a non-toxic, water-soluble green dye to provide a means of metering for even distribution. Tackifier should consist of seed husks (Psyillium) such that, when combined with wood fiber and water, it should have the property of even dispersion and suspension.

Seeding should be done as early in the "planting window" as possible. Biotechnical construction and fall planting of transplants and unrooted cuttings should be done before grass seeding. If construction schedules dictate spring seeding, this seeding should be accomplished as early as possible

Grading, gully or rill repairs and biotechnical installations should be accomplished prior to seeding. Graded slopes should be left rough. All physical erosion control improvements, such as water diversion channels, earth berms, dikes, ditches, should be installed prior to grass seeding.

The fertilizer should be applied so as to be evenly distributed. Fertilizers should not be applied more than two weeks prior to seeding. Fertilizer should be applied prior to hand raking or dragging.

Grass seed should be uniformly distributed at the rate recommended for the particular species used (50 pounds of pure live seed per acre or 1.1 lbs/1000 sq. ft., for example). Seed should be broadcast by mechanical trend or power-operated spreaders. The area should be hand raked or dragged after seeding to partially cover the bed. Care should be exercised to avoid damaging the transplants and cuttings.

All grass seeded areas should be mulched within two working days following seeding unless prevented by weather and approved by the project engineer. Straw should be uniformly distributed at the rate of not less than two nor more then three tons per acre. Straw may be applied in two ways, either as whole straw applied by hand or with a straw blower. Spreading of whole straw should be by hand. Straw should be crimped into the ground using digging or tile spades to avoid damaging transplants, or it may be anchored with tackifier. All straw applied with a straw blowing machine should be anchored with tackifier described below. Application by blower should be done only when wind velocities are low enough to prevent blowing of the straw off the slope. Such applications should be anchored with tackifier on the day of application.

Tackifier should be mixed to form a slurry and applied by hydroseeder or similar equipment equipped with a continuous agitation system of sufficient operating capacity to produce a homogeneous slurry. The discharge system should be capable of applying the slurry at a continuous and uniform rate. Mixing, agitation, and application should be carried out as a continuous operation.

Irrigation Systems

A planned irrigation system in which all necessary facilities are installed for efficiently applying water to the vegetation components of a stabilization or restoration project is often necessary and should always be considered. Reestablishment of vegetation lost to drought is very costly and easily avoided. Irrigation is typically required only in the first one or two growing seasons, so systems that can be removed and reused for other projects are desirable. Irrigation plans should be based on an evaluation of the site and the expected operating conditions. The soils and topography must be suitable for the type of irrigation selected. The water supply must be sufficient in quantity and quality.

Irrigation Options

Three principle types of irrigation systems are used for restoration and stabilization projects: trickle or drip systems, spray systems, and mobile systems. Flood systems (a fourth option) are generally more applicable to agricultural crops than streambank and riparian projects and are not covered in this handbook. Table 7.8 presents relative comparisons of the merits and disadvantages of each system.

Trickle systems apply water directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, perforated pipe) operated under low pressure. The applicators can be placed on or below the surface of the ground. Trickle systems are the most efficient way to water maintain soil moisture within the range for good plant growth and without excessive water loss, erosion, reduction in water quality, or salt accumulation.

As the name implies, spray systems use sprinkler heads and pressure to distribute water over vegetation in a fashion that mimics rainfall. Spray systems can be further divided into underground, surface, and overhead systems depending on the location of the piping systems. Underground systems tend to be costly and are useful only in cases where permanence is required or where vandalism may present a problem.

Mobile irrigation systems can be the least expensive option for watering plants used in bioengineering or restoration projects. This option includes removable systems ranging from large long-range sprinklers used in conjunction with fire hoses to standard garden hoses and consumer-grade sprinklers supplied with low-head effluent pumps placed in the adjacent stream.

Table 7.8 Comparison of Irrigation Systems

Trickle or Drip Irrigation	*Underground Spray Systems*	*Surface/Overhead Spray Systems*	*Mobile Irrigation*
Affordable	Expensive	Moderate Cost	Inexpensive
Simple Installation	Moderate Installation	Simple Installation	No Installation
Unobtrusive	Unobtrusive	Unattractive	Unobtrusive
Vandal Prone	Vandal Proof	Vandal Prone	Vandal Proof
Convenient Use	Convenient Use	Convenient Use	Inconvenient Use
Temporary/Movable	Permanent/Immovable	Temporary/Movable	Temporary/Highly Mobile
Not Suitable for Herbaceous	Suitable for all vegetation	Suitable for all vegetation	Suitable for all vegetation
Erosion Resistant	Promotes Erosion	Promotes Erosion	Variable Erosion
Moderate Freeze Resistant	Freeze Resistant	Freeze Susceptible	Freeze Resistant
Low Volume/Pressure	High Volume/Pressure	High Volume/Pressure	Low Volume/Pressure

PLANNING

Availability of water will dictate many decisions regarding the design and layout of an irrigation system for a restoration or stabilization project. The size of the project, its location, and convenience factors will dictate the optimum source when more than one option is available. Generally, water sources include:

- Potable Water
- Surface Water
- Excavated Wells
- Drilled Wells
- Point Wells
- Cisterns

To efficiently convey and distribute irrigation water to the point of application without causing excessive erosion, water losses, or reduction in water quality, the project site must be suitable for irrigation. Water supplies must be sufficient in quantity and quality to make irrigation practical for the vegetation to be grown and also must be adequate for the water application methods to be used. Considerations related to water quantity and quality include:

Quantity

- Water budget effects, especially volumes and rates of infiltration, evaporation, transpiration, deep percolation, and ground water recharge.
- Potential for a change in plant growth and transpiration because of changes in the volume of soil water.
- Effects on the water table in maintaining a suitable root zone for the desired vegetation.
- Potential ability for irrigation water management of difficult soils and terrain through control of water within the root zone.

Quality

- Effects of nutrients and pesticides on surface and ground water quality.
- Effects on the movement of dissolved substances below the root zone or to ground water.
- Effects of water management on salinity of soils, soil water, or aquifers.
- Potential for development of saline seeps or other salinity problems resulting from increased infiltration near restrictive layers.

DESIGN

Code requirements governing the design and installation of irrigation systems exist in most locations. The extent and nature of the codes vary, but a permit is generally needed. In many western states, allocation of water rights can be a constraint as well. Be sure to check with local government agencies regarding water use restrictions. In urban environments, the three most common code requirements are 1) backflow protection (required only when potable water sources are used), 2) limitations on the types of materials used, and 3) investigation of underground utilities and trenching limitations. Codes are typically less stringent in rural areas.

Manufacturers of irrigation system supplies generally provide detailed design guidance and their recommendations should be followed. Design Requirements for a standard Trickle/Drip Systems follow as an example.

Depth of application. The net depth of application should be sufficient to replace the water used by the vegetation through evapotranspiration (ET) during the peak use period or critical growth stage without depleting the soil moisture in the root zone of the vegetation below the minimum level established for optimum growth. The gross depth should be determined by dividing the net depth by the application efficiency provided by the manufacturer.

Capacity. The design capacity of trickle irrigation systems should be adequate to meet moisture demands during peak use period of each plant to be irrigated in the design area. The capacity should include an allowance for reasonable water losses during application periods. The system should have the capacity to apply a stated amount of water to the design area in a specified net operating period. The design area may be less than 100 percent of the field area but not less than the mature vegetation root zone area.

Design application rate. The design rate of application should be within a range established by the minimum practical discharge rate of the applicators (orifices, emitters, porous tubing, perforated pipe) and the maximum rate consistent with the intake rate of the soil. The application rate should be expressed in gallons per hour per emitter or orifice or per foot of porous tubing or perforated pipe. The discharge rate of orifices, emitters, porous tubing, or perforated pipe may be determined from the manufacturer's data relating to discharge and operating pressure. Emitters should be located to provide an overlap of the wetting pattern within the root zone.

Lateral lines. Lateral lines should be so designed that when operating at the design pressure, the discharge rate of any applicator served by the lateral will not exceed a variation of $\pm$ 15 percent of the design discharge rate.

Main lines. Main lines and submains should be designed to supply water to all lateral lines at a flow rate and pressure not less than the minimum design requirements of each lateral line. Adequate pressure must be provided to overcome friction losses in the pipelines and in all appurtenances, such as valves and filters. Mains and submains should be designed and installed according to local provisions or standards for irrigation pipelines.

Filters. A filtration system should be provided at the system inlet if a surface water source is selected. If available, recommendations of the emitter manufacturer should be used in selecting the filtration system. In the absence of the manufacturer's recommendations, the net opening diameter of the filter should be not larger than one-fourth the diameter of the emitter opening.
All injectors, such as fertilizer injectors, should be installed upstream of the system filter, except for systems having injectors equipped with separate filters. The filter system should permit flushing, cleaning, or replacement as required without introducing contaminants or foreign particles into the trickle system.

Table 7.9 Dripline characteristics as a function of soil and vegetation type.

	EMITTER SPACING	ROW SPACING	EMITTER FLOW	BURIAL DEPTH
MEDIUM SAND				
TREES/SHRUBS/GROUNDCOVER	12"	18"	1 GPH	4"
GRASS	12"	12"	1GPH	6"
LOAM				
TREES/SHRUBS/GROUNDCOVER	18"	18"	1GPH	6"
GRASS	12"	18"	1 GPH	6"
CLAY LOAM				
TREES/SHRUBS/GROUNDCOVER	18"	24"	1/2 GPH	6"
GRASS	18"	18"	1/2 GPH	6"
CLAY				
TREES/SHRUBS/GROUNDCOVER	18"	24"	1/2 GPH	6"
GRASS	18"	18"	1/2 GPH	6"

System Pressure

Landscape irrigation system performance is directly related to system pressure. Proper pressure results in water conservation, healthy plant material and system durability. Inappropriate pressure is a primary cause of poor irrigation performance and leads to poor water coverage of some zones and drought stress to vegetation. It is always better to have excessive pressure than inadequate pressure, since pressure regulation costs less than trying to overcome a low-pressure problem.

Many irrigation systems rely exclusively on delivered pressure. When this fluctuates, so will the coverage areas and precipitation rates of the sprinklers. A 10 percent pressure difference between laterals can cause a 5 percent difference in precipitation rates. Contract specifications should require a 15 percent maximum variation in pressure under operating conditions.

Excess system pressures are best managed through the use of pressure regulators. Using flow control for pressure control almost always results in uneven pressure and poor uniformity. Most valves come with a flow control knob or dial on top of the valve, which is tempting to use as a pressure regulator when the pressure is too great. Unfortunately, this device responds to changes in pressure and does not compensate for them. The best techniques to overcome inadequate pressure are:

- Increase pressure.
- Use shorter laterals or add a valve and split the lateral into two separate stations.
- Reduce the nozzle or oriface sizes on all heads on the zone by one size. This reduces the amount of water being applied overall, but it can improve uniformity.
- Adding new heads or laterals to an existing valve will affect pressure and may increase problems during the peak stress months. Additions to an existing system should consider both static and dynamic pressure, pipe size, sprinkler head type and flow, and distances between existing heads and laterals.

Special Considerations for Slopes.

Driplines should be located parallel to the contour of slopes whenever possible. Since subsurface run-off occurs on sloped areas, consideration must be given to dripline density from the top to the bottom of the slope (Slopes greater than 3 percent). The dripline on the top two thirds of the slope should be spaced at the manufacturer's recommended spacings for the soil type and plant material in question and on the lower one third the driplines should be spaced twenty five percent wider. The last dripline can also be eliminated on slopes exceeding 5 percent. For areas exceeding ten feet in elevation change, zone the lower one third of the slope separately from the upper two thirds to help control drainage.

When utilizing non pressure-compensating driplines, elevation differences of five feet or more require separate zoning or individual pressure regulators for each six foot difference on uniform slopes. When working with elevation differences of five feet or more within a zone, it is best to use a pressure compensating dripline to equalize pressure differentials created by the elevation differences. Subsurface irrigation zones must have a vacuum relief valve at the highest point. This will eliminate the vacuum created by low line drainage that causes soil ingestion. This is especially crucial when the dripline laterals must be placed perpendicular to the contour of the slope. It is also necessary to connect all dripline laterals within the elevated area with an air relief lateral.

Conservation measures.

A variety of measures can be applied to reduce water use including:
Controllers that have multiple programs allow the differential application of irrigation water to areas with different requirements.
A rainguard measures rainfall and stops operation of the irrigation controller if rainfall amounts are sufficient within a given time period.
A moisture meter that measures soil moisture with a probe can indicate water need, and automated meters can prevent the system from operating not needed.

CONSTRUCTION

Drip irrigation lines are generally installed subsurface except for temporary systems. Several trenching options are available. Table 7.10 provides advantages and disadvantages of the more common trenching measures. In addition to the general site preparation requirements, special soil preparation is required to obtain proper performance from a drip irrigation system.

Soil Preparation.

As with all types of landscape irrigation systems, properly prepared soil is necessary to provide a consistently homogenous foundation for proper plant establishment, root growth and water distribution. Heavily compacted and layered soils should be ripped and tilled at a uniform twelve-inch depth to improve the homogeneity of the soil.

Soil and water analyses are recommended when the soil texture, soil Ph, and water quality are in doubt. This is necessary for recommendations for soil amendments and water treatment when necessary. If possible, pre-irrigate the installation site when the soil is too dry to till and trench. This makes tilling and installation much easier and trouble free.

Installation Steps

Installation should be in accordance with manufacturer's recommendations, but generally follows these steps:

1. Assemble and install filter, remote control valve, and pressure regulating valve assembly(s).
2. Assemble and install supply header(s). Tape and or plug all open connections to prevent debris contamination.
3. Assemble and install exhaust header(s). Tape or plug all open connections to prevent debris contamination.
4. Install dripline laterals. Tape or plug all open ends while installing the dripline to prevent debris contamination.
5. Install air vacuum relief valve(s) at the zones highest point(s).
6. Thoroughly flush supply header(s) and connect dripline laterals while flushing.
7. Thoroughly flush dripline laterals and connect to exhaust header(s) or interconnecting laterals while flushing.
8. Thoroughly flush exhaust header(s) and install line flushing valves.
9. Test system operation and performance.

Table 7.10 Considerations for trenching methods.

INSERTION METHOD	*ADVANTAGES*	*DISADVANTAGES*
Hand trenching or backfilling.	- Handles severe slopes and confined areas. - Uniform depth.	- Slow. - Labor intensive. - Disrupts existing turf and ground.
Oscillating or Vibrating plow (cable or pipe pulling type).	- Fast in small to medium installations. - Minimal ground disturbance. - No need to backfill the trench.	- Depth has to be monitored closely. - Cannot be used on steeper slopes (20%). - Requires practice to set and operate adequately. - Tends to "stretch" pipe.
Trenching machine. (Ground Hog, Kwik- Trench, E-Z Trench).	- Faster than hand trenching. - May use the 1" blade for most installations. - Uniform depth.	- Slower, requires labor. - Disrupts surface of existing turf. - Back fill required.
Tractor mounted 3-point hitch, insertion implement.	- Fastest. Up to four plow attachments with reels. - A packer roller compacts soil over the pipe.	- Only suitable for area large enough to maneuver a small tractor.

OPERATION AND MAINTENANCE

Irrigation systems must be designed as an integral part of an overall plan of restoration or conservation land use. The capabilities and needs of the project sponsor will dictate their potential to adequately operate and maintain the irrigation system.

Irrigation systems need to be checked on a regular basis, especially during summer months. The system should be monitored to ensure that it is in good repair, with no leaks, and that the sprinklers are adjusted to minimize misdirected spray. Low-volume spray heads should be used, and watering stopped if puddling and runoff is observed. Watering should be accomplished before 9 a.m. when it is generally less windy and cooler.

Appendix A
Stream Restoration Glossary

OVERVIEW

Following is a glossary of terms commonly used in stream restoration. Not all of the terms appear in this handbook, and the glossary is intended as a general reference.

TERMS

Abatement -- Reducing the degree or intensity of, or eliminating, pollution.

Ablation -- The process by which ice and snow waste away as a result of melting and/or evaporation.

Acid Rain -- Rainfall with a pH of less than 7.0. Long-term deposition of these acids is linked to adverse effects on aquatic organisms and plant life in areas with poor neutralizing (buffering) capacity.

Acidic -- The condition of water or soil that contains a sufficient amount of acid substances to lower the pH below 7.0.

Acre -- A measure of area equal to 43,560 square feet (4,046.87 square meters). One square mile equals 640 acres.

Acre-Foot (af) -- A quantity or volume of water covering one acre to a depth of one foot; equal to 43,560 cubic feet or 325,851 gallons.

Active Storage Capacity -- The total usable reservoir capacity available for seasonal or cyclic water storage. It is gross reservoir capacity minus inactive storage capacity.

Aeration -- Any active or passive process by which intimate contact between air and liquid is assured, generally by spraying liquid in the air, bubbling air through water, or mechanical agitation of the liquid to promote surface absorption of air.

Aerobic -- Characterizing organisms able to live only in the presence of air or free oxygen, and conditions that exist only in the presence of air or free oxygen. Contrast with Anaerobic.

Affluent (Stream) -- A stream or river that flows into a larger one; a Tributary.

Afterbay -- A reservoir that regulates fluctuating discharges from a hydroelectric power plant or a pumping plant.

Aggradation -- A progressive buildup or raising of the channel bed and floodplain due to sediment deposition. The geologic process by which stream beds are raised in elevation and floodplains are formed. Aggradation is an indicator that a change in the stream's discharge and/or bedload characteristics is taking place. Opposite of degradation.

Algae -- Microscopic plants that grow in sunlit water containing phosphates, nitrates, and other nutrients. Algae, like all aquatic plants, add oxygen to the water and are important in the fish food chain.

Alluvial -- Deposited by running water.

Alluvium -- Sediment or loose material such as clay, silt, sand, gravel, and larger rocks deposited by moving water.

Anabranch -- A diverging branch of a river which re-enters the main stream.

Anadromous -- Pertaining to fish that spend a part of their life cycle in the sea and return to freshwater streams to spawn.

Angler-day -- The time spent fishing by one person for any part of a day.

Aquaduct -- A pipe or conduit made for bringing water from a source.

Aquatic ecosystem -- Any body of water, such as a stream, lake or estuary, and all organisms and nonliving components within it, functioning as a natural system.

Aquatic habitat -- Habitat that occurs in free water.

Aquifer -- A geologic formation that stores and transmits water and yields significant quantities of water to wells and springs.

Arid -- A term describing a climate or region in which precipitation is so deficient in quantity or occurs so infrequently that intensive agricultural production is not possible without irrigation.

Armoring -- A natural process where an erosion-resistant layer of relatively large particles is established on the surface of the streambed through removal of finer particles by stream flow. A properly armored streambed generally resist movement of bed material at discharges up to approximately 3/4 bankfull depth.

Artificial recharge -- Addition of surface water to a ground water reservoir by human activity, such as putting surface water into spreading basins. See also ground water recharge, recharge basin.

Augmentation (of stream flow) -- Increasing steam flow under normal conditions, by releasing storage water from reservoirs.

Average annual runoff -- For a specified area, it is the average value of annual runoff amounts calculated for a selected period of record that represents average hydrologic conditions.

Average year supply -- The average annual supply of a water development system over a long period.

Average year water demand -- Demand for water under average hydrologic conditions for a defined level of development.

Avulsion -- A change in channel course that occurs when a stream suddenly breaks through its banks - typically bisecting an over extended meander arc.

Backwater -- (1) A small, generally shallow body of water attached to the main channel, with little or no current of its own. (2) A condition in subcritical flow where the water surface elevation is raised by downstream flow impediments.

Backwater pool -- A pool that formed as a result of an obstruction like a large tree, weir, or boulder.

Bank stability -- The ability of a stream bank to counteract erosion or gravity forces.

Bankfull channel depth -- The maximum depth of a channel within a riffle segment when flowing at a bankfull discharge.

Bankfull channel width -- The top surface width of a stream channel when flowing at a bankfull discharge.

Bankfull discharge -- The stream discharge corresponding to the water stage which first overtops the natural banks. This flow occurs, on average, about once every 1 to 2 years.

Bankfull width -- The width of a river or stream channel between the highest banks on either side of a stream.

Bar -- An accumulation of alluvium(usually gravel or sand) caused by a decrease in sediment transport capacity on the inside of meander bends or in the center of an overwide channel.

Barrier -- A physical block or impediment to the movement or migration of fish, such as a waterfall (natural barrier) or a dam (man-made barrier).

Base flow -- The sustained portion of stream discharge that is drawn from natural storage sources, and not effected by human activity or regulation.

Bed Load -- Sediment moving on or near the stream bed and transported by jumping, rolling, or sliding on the bed layer of a stream. See also suspended load.

Bed material -- The sediment mixture of which a streambed is composed.

Bed material load -- That portion of the total sediment load with sediments of a size found in the stream bed.

Bed Roughness -- A measure of the irregularity of the stream bed as it contributes to flow resistance. Commonly expressed as a Manning "n" value.

Bed Slope -- The inclination of the channel bottom, measured as the elevation drop per unit length of channel.

Benthic invertebrates -- Aquatic animals without backbones that dwell on or in the bottom sediments of fresh or salt water. Examples: clams, crayfish, and a wide variety of worms.

Benthos -- All the plant and animals living on or closely associated with the bottom of a body of water.

Best management practice (BMP) -- Conservation measures intended to minimize or mitigate impacts from a variety of landuse activities.

Biota -- All living organisms of a region, as in a stream or other body of water.

Blowdown -- Trees felled by high winds.

Bog -- Freshwater wetlands that are poorly drained and characterized by a buildup of peat.

Boulder -- A large substrate particle that is larger that cobble, 256 mm in diameter.

Brackish water -- Generally, water containing dissolved minerals in amounts that exceed normally acceptable standards for municipal, domestic, and irrigation uses. Considerably less saline than sea water. Also, Marine and Estuarine waters with Mixohaline salinity (0.5 to 30 due to ocean salts). Water containing between 1,000-4,000 parts per million (PPM) Total Dissolved Solids TDS). The term brackish water is frequently interchangeable with Saline Water. The term should not be applied to inland waters.

Braided channel -- A stream characterized by flow within several channels which successively meet and divide. Braiding often occurs when sediment loading is too large to be carried by a single channel.

Braiding (of River Channels) -- Successive division and rejoining of riverflow with accompanying islands.

Buffer strip -- A barrier of permanent vegetation, either forest or other vegetation, between waterways and land uses such as agriculture or urban development, designed to intercept and filter out pollution before it reaches the surface water resource.

Canal -- A constructed open channel for transporting water.

Canopy -- A layer of foliage in a forest stand. This most often refers to the uppermost layer of foliage, but it can be used to describe lower layers in a multistoried stand. Leavs, branches and vegetation that are above ground and/or water that provide shade and cover for fish and wildlife.

Cascade -- A short, steep drop in stream bed elevation often marked by boulders and agitated white water.

Catchment -- (1) The catching or collecting of water, especially rainfall. (2) A reservoir or other basin for catching water. (3) The water thus caught. (4) A watershed.

Channel -- An area that contains continuously or periodically flowing water that is confined by banks and a stream bed.

Channelization -- The process of changing (usually straightening) the natural path of a waterway.

Clay -- Substrate particles that are smaller than silt and generally less than 0.004 mm in diameter.

Closed basin -- A basin whose topography prevents surface outflow of water. It is considered to be hydrologically closed if neither surface nor underground outflow of water can occur.

Coarse woody debris (CWD) -- Portion of a tree that has falled or been cut and left in the woods. Usually refers to pieces at least 20 inches in diameter.

Cobble -- Substrate particles that are smaller than boulders and larger than gravels, and are generally 64-256 mm in diameter. Can be further classified as small and large cobble.

Confined aquifer -- A water-bearing subsurface stratum that is bounded above and below by formations of impermeable, or relatively impermeable, soil or rock.

Confluence -- (1) The act of flowing together; the meeting or junction of two or more streams; also, the place where these streams meet. (2) The stream or body of water formed by the junction of two or more streams; a combined flood.

Conifer -- A tree belonging to the order Gymnospermae, comprising a wide range of trees that are mostly evergreens. Conifers bear cones (hence, coniferous) and needle-shaped or scalelike leaves.

Conjunctive use -- The operation of a ground water basin in combination with a surface water storage and conveyance system. Water is stored in the ground water basin for later use by intentionally recharging the basin during years of above-average water supply.

Conservation -- The process or means of achieving recovery of viable populations.

Conservation area -- Designated land where conservation strategies are applied for the purpose of attaining a viable plant or animal population.

Conservation recommendations -- Suggestions by the Fish and Wildlife Service or National Marine Fisheries Service in biological opinions regarding discretionary measures to minimize or avoid adverse effects on a proposed action of federally listed threatened or endangered species or designated critical habitat.

Conservation strategy -- A management plan for a species, group of species, or ecosystem that prescribes standards and guidelines that if implemented provide a high likelihood that the species, groups of species, or ecosystem, with its full complement of species and processes, will continue to exist well-distributed throughout a planning area, i.e., a viable population.

Contaminate -- To make impure or unclean by contact or mixture.

Contiguous habitat -- Habitat suitable to support the life needs of species that is distributed continuously or nearly continuously across the landscape.

Core area -- The area of habitat essential in the breeding, nesting and rearing of young, up to the point of dispersal of the young.

Creel census survey -- The collection of data concerning the number of fish caught by sport fishers on a particular stream or in a particular area.

Critical habitat -- Under the Endangered Species Act, critical habitat is defined as (1) the specific areas within the geographic area occupied by a federally listed species on which are found physical and biological features essential to the conservation of the species, and that may require special management considerations or protections; and (2) specific areas outside the geographic area occupied by a listed species, when it is determined that such areas are essential for the conservation of the species.

Critical Shear Stress -- The minimum amount of shear stress exerted by stream currents required to initiate soil particle motion. Because gravity also contributes to stream bank particle movement but not on stream beds, critical shear stress along streambanks is less than for stream beds.

Crown -- The upper part of a tree or other woody plant that carries the main system of branches and the foliage.

Crown cover -- The degree to which the crowns of trees are nearing general contact with one another.

Cubic feet per second (cfs) -- A unit used to measure water flow. One cfs is equal to 449 gallons per minute.

Culvert -- A buried pipe that allows streams, rivers, or runoff to pass under a road.

Debris flow -- A rapid moving mass of rock fragments, soil, and mud, with more that half of the particles being larger that sand size.

Debris torrent -- Rapid movement of a large quantity of materials (wood and sediment) down a stream channel during storms or floods. This generally occurs in smaller streams and results in scouring of streambed.

Deciduous -- Trees and plants that shed their leaves at the end of the growing season.

Decomposer -- Any of various organisms (as many bacteria and fungi) that feed on and break down organic substances (such as dead plants and animals).

Decomposition -- The breakdown of matter by bacteria and fungi, changing the chemical makeup and physical appearance of materials.

Deep percolation -- The percolation of water through the ground and beyond the lower limit of the root zone of plants into a ground water aquifer.

Degradation -- (1) A progressive lowering of the channel bed due to scour. Degradation is an indicator that that a change in the stream's discharge and/or sediment load is occurring. The opposite of aggradation. (2) A decrease in value for a designated use.

Dependable supply -- The annual average quantity of water that can be delivered during a drought period.

Depletion -- A water use term. The water consumed within a service area and no longer available as a source of supply. For agriculture and wetlands, it is ETAW (and ET of flooded wetlands) plus irrecoverable losses. For urban water use, it is ETAW (water applied to landscaping or home gardens), sewage effluent that flows to a salt sink, and incidental ET losses. For instream use, it is the amount of dedicated flow that becomes ground water and is not available for reuse.

Dike -- (1) (Engineering) An embankment to confine or control water, especially one built along the banks of a river to prevent overflow of lowlands; a levee. (2) A low wall that can act as a barrier to prevent a spill from spreading. (3) (Geology) A tabular body of igneous (formed by volcanic action) rock that cuts across the structure of adjacent rocks or cuts massive rocks.

Discount rate -- The interest rate used in evaluating water (and other) projects to calculate the present value of future benefits and future costs or to convert benefits and costs to a common time basis.

Dissolved gas concentrations -- The amount of chemicals normally occurring as gases, such as nitrogen and oxygen, that are held in solution in water, expressed in units such as milligrams of the gas per liter of liquid. Supersaturation occurs when these solutions exceed the saturation level of the water (beyond 100 percent).

dissolved organic compounds carbon substances dissolved in water.

Dissolved Oxygen (DO) -- The amount of free (not chemically combined) oxygen dissolved in water, wastewater, or other liquid, usually expressed in milligrams per liter, parts per million, or percent of saturation.

Ditch -- A long narrow trench or furrow dug in the ground, as for irrigation, drainage, or a boundary line.

Diversion -- The transfer of water from a stream, lake, aquifer, or other source of water by a canal, pipe, well, or other conduit to another watercourse or to the land, as in the case of an irrigation system.

Diversion channel -- (1) An artificial channel constructed around a town or other point of high potential flood damages to divert floodwater from the main channel to minimize flood damages. (2) A channel carrying water from a diversion dam.

Drainage area - The total surface area upstream of a point on a stream that drains toward that point. Not to be confused with watershed. The drainage area may include one or more watersheds.

Drainage basin -- The total area of land from which water drains into a specific river.

Dredging -- Removing material (usually sediments) from wetlands or waterways, usually to make them deeper or wider.

Drought -- Generally, the term is applied to periods of less than average or normal precipitation over a certain period of time sufficiently prolonged to cause a serious hydrological imbalance resulting in biological losses (impact flora and fauna ecosystems) and/or economic losses (affecting man). In a less precise sense, it can also signify nature's failure to fulfill the water wants and needs of man.

Dry Wash -- A streambed that carries water only during and immediately following rainstorms.

Ecology -- The study of the interrelationships of living organisms to one another and to their surroundings.

Economic demand -- The consumer's willingness and ability to purchase some quantity of a commodity based on the price of that commodity.

Ecosystem management -- A strategy or plan to manage ecosystems to provide for all associated organisms, as opposed to a strategy or plan for managing individual species.

Ecosystem -- Recognizable, relatively homogeneous units, including the organisms they contain, their environment, and all the interactions among them.

Eddy -- A circular current of water, usually resulting from an obstruction.

Effluent -- (1) Something that flows out or forth, especially a stream flowing out of a body of water. (2) (Water Quality) Discharged wastewater such as the treated wastes from municipal sewage plants, brine wastewater from desalting operations, and coolant waters from a nuclear power plant.

Embankment -- An artificial deposit of material that is raised above the natural surface of the land and used to contain, divert, or store water, support roads or railways, or for other similar purposes.

Energy Dissipation -- The loss of kinetic energy of moving water due to internal turbulence, bottom friction, large rocks, debris, or other obstacles that impede flow.

Enhancement -- Emphasis on improving the value of particular aspects of water and related land resources.

Environment -- The sum of all external influences and conditions affecting the life and development of an organism or ecological community; the total social and cultural conditions.

Environmental analysis -- An analysis of alternative actions and their predictable short-term and long-term environmental effects, incorporating physical, biological, economic, and social considerations.

Environmental assessment (EA) -- A systematic analysis of site-specific activities used to determine whether such activities have a significant effect on the quality of the human environment and whether a formal environmental impact statement is required; and to aid an agency's compliance with the National Environmental Policy Act when no environmental impact statement is necessary.

Environmental impact -- The positive or negative effect of any action upon a give area or resource.

Environmental impact statement (EIS) -- A formal document to be filed with the Environmental Protection Agency that considers significant environmental impacts expected from implementation of a major federal action.

Ephemeral Streams -- Streams which flow only in direct response to precipitation and whose channel is at all times above the water table.

Erosion -- Wearing away of rock or soil by the gradual detachment of soil or rock fragments by water, wind, ice, and other mechanical, chemical, or biological forces.

Estuary -- A coastal body of water that is semi-enclosed, openly connected with the ocean, and mixes with freshwater drainage from land.

Eutrophic -- Usually refers to a nutrient-enriched, highly productive body of water.

Eutrophication -- The process of enrichment of water bodies by nutrients.

Evaporation -- The physical process by which a liquid (or a solid) is transformed to the gaseous state. In Hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

Evapotranspiration (ET) -- The quantity of water transpired (given off), retained in plant tissues, and evaporated from plant tissues and surrounding soil surfaces. Quantitatively, it is usually expressed in terms of depth of water per unit area during a specified period of time.

Evapotranspiration of applied water (ETAW) -- The portion of the total evapotranspiration provided by irrigation.

Fill -- (1) (Geology) Any sediment deposited by any agent such as water so as to fill or partly fill a channel, valley, sink, or other depression. (2) (Engineering) Soil or other material placed as part of a construction activity.

Final environmental impact statement (FEIS) -- The final report of environmental effects of proposed action on an area of land. This is required for major federal actions under Section 102 of the National Environmental Policy Act. It is a revision of the draft environmental impact statement to include public and agency responses to the draft.

Flash Flood -- A sudden flood of great volume, usually caused by a heavy rain. Also, a flood that crests in a short length of time and is often characterized by high velocity flows.

Floodplain -- Land built of sediment that gets covered with water as a result of the flooding of a nearby stream.

Floodplain (100-year) -- The area adjacent to a stream that is on average inundated once a century.

Flow -- The amount of water passing a particular point in a stream or river, usually expressed in cubic-feet per second (cfs).

Flow augmentation -- Increased flow from release of water from storage dams.

Fluvial -- Migrating between main rivers and tributaries. Of or pertaining to streams or rivers.

Fluvial -- Pertaining to streams or produced by stream action.

Ford -- A shallow place in a body of water, such as a river, where one can cross by walking or riding on an animal or in a vehicle.

Forebay -- A reservoir or pond situated at the intake of a pumping plant or power plant to stabilize water levels; also a storage basin for regulating water for percolation into ground water basins.

Forest canopy -- The cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody growth.

Fry -- A recently hatched fish.

Gabion -- A wire basket or cage that is filled with gravel or cobble and generally used to stabilize stream banks.

Gaging station -- A particular site in a stream, lake, reservoir, etc., where hydrologic data are obtained.

Gallons per minute (gpm) -- A unit used to measure water flow.

Geographic information system (GIS) -- A computer system capable of storing and manipulating spatial data.

Geomorphology -- A branch of both physiography and geology that deals with the form of the earth, the general configuration of its surface, and the changes that take place due to erosion of the primary elements and in the buildup of erosional debris

Glide -- A section of stream that has little or no turbulence.

Gradient -- Vertical drop per unit of horizontal distance.

Grass/Forb -- Herbaceous vegetation.

Gravel -- Rock fragments larger than sand and smaller than cobbles.

Gray Water -- Waste water from a household or small commercial establishment which specifically excludes water from a toilet, kitchen sink, dishwasher, or water used for washing diapers.

Reservoir capacity -- The storage capacity available in a reservoir for all purposes, from the streambed to the normal maximum operating level. Includes dead (or inactive) storage, but usually excludes surcharge (water temporarily stored above the elevation of the top of the spillway).

Ground water basin -- A ground water reservoir, defined by an overlying land surface and the underlying aquifers that contain water stored in the reservoir. In some cases, the boundaries of successively deeper aquifers may differ and make it difficult to define the limits of the basin.

Ground water overdraft -- The condition of a ground water basin in which the amount of water withdrawn by pumping exceeds the amount of water that recharges the basin over a period of years during which water supply conditions approximate average.

Ground water prime supply -- The long-term average annual percolation into the major ground water basins from precipitation falling on the land and from flows in rivers and streams.

Ground water recharge -- Increases in ground water storage by natural conditions or by human activity. See also artificial recharge.

Ground water storage capacity -- The space or voids contained in a given volume of soil and rock deposits.

Ground water table -- The upper surface of the zone of saturation, except where the surface is formed by an impermeable body.

Ground water -- Subsurface water and underground streams that can be collected with wells, or that flow naturally to the earth's surface though springs.

Habitat -- The local environment in which organisms normally live and grow.

Habitat conservation plan (HCP) -- An agreement between the Secretary of the Interior and either a private entity or a state that specifies conservation measures that will be implemented in exchange for a permit that would allow taking of a threatened or endangered species.

Habitat diversity -- The number of different types of habitat within a given area.

Habitat fragmentation -- The breaking up of habitat into discrete islands through modification or conversion of habitat by management activities.

Hardpan -- A layer of nearly impermeable soil beneath a more permeable soil, formed by natural chemical cementing of the soil particles.

Hatch box -- A device used to incubate relatively small numbers of fish eggs. The hatch box is usually located adjacent to a stream, which supplies the box with water.

Hazardous materials -- Anything that poses a substantive present or potential hazard to human health or the environment when improperly treated, stored, transported, disposed of, or otherwise managed.

Headwater -- Referring to the source of a stream or river

Heavy metals -- Metallic elements with high atomic weights, e.g., mercury, chromium, cadmium, arsenic, and lead. They can damage living things at low concentrations and tend to accumulate in the food chain.

Hydraulic Gradient -- The slope of the water surface. See also stream bed gradient.

Hydraulic Radius -- The cross-sectional area of a stream divided by the wetted perimeter.

Hydric -- Wet.

Hydrograph -- A curve showing stream discharge over time.

Hydrologic balance -- An accounting of all water inflow to, water outflow from, and changes in water storage within a hydrologic unit over a specified period of time.

Hydrologic region -- A study area, consisting of one or more planning subareas, which has a common hydrologic character.

Hydrologic unit -- A distinct watershed or river basin defined by an 8-digit code.

Hydrology -- The scientific study of the water of the earth, its occurrence, circulation and distribution, its chemical and physical properties, and its interaction with its environment, including its relationship to living things.

Hyporheic zone -- The area under the stream channel and floodplain that has a free exchange of ground water with the surface waters of the stream.

Incised River -- A river that erodes its channel by the process of degradation to a lower base level than existed previously or is consistent with the current hydrology.

Infiltration (soil) -- The movement of water through the soil surface into the soil.

Inflow -- Water that flows into a stream, lake, reservoir or forebay during a specified period.

Instream cover -- The layers of vegetation, like trees, shrubs, and overhanging vegetation, that are in the stream or immediately adjacent to the wetted channel.

Instream flows -- (1) Portion of a flood flow that is contained by the channel. (2) A minimum flow requirement to maintain ecological health in a stream.

Instream use -- Use of water that does not require diversion from its natural watercourse. For example, the use of water for navigation, recreation, fish and wildlife, aesthetics, and scenic enjoyment.

Intermittent stream -- Any nonpermanent flowing drainage feature having a definable channel and evidence of scour or deposition. This includes what are sometimes referred to as ephemeral streams if they meet these two criteria.

Invertebrate drift -- Stream and terrestrial invertebrates that float with the current.

Irrigation diversion -- Generally, a ditch or channel that deflects water from a stream channel for irrigation purposes.

Irrigation efficiency -- The efficiency of water application and use. Computed by dividing evapotranspiration of applied water by applied water and converting the result to a percentage. Efficiency can be computed at three levels: farm, district, or basin.

Irrigation return flow -- Applied water that is not transpired, evaporated, or deep-percolated into a ground water basin but that returns to a surface water supply.

Key watershed -- As defined by National Forest and Bureau of Land Management District fish biologists, a watershed containing (1) habitat for potentially threatened species or stocks of anadromous salmonids or other potentially threatened fish, or (2) greater than 6 square miles with high-quality water and fish habitat.

Landscape -- A heterogenous land area with interacting ecosystems that are repeated in similar form throughout.

Landscape diversity -- The size, shape, and connectivity of different ecosystems across a large area.

Landscape features -- The land and water form vegetation, and structures that compose the characteristic landscape.

Landslide -- A movement of earth mass down a steep slope.

Large woody debris (LWD) -- Pieces of wood larger than 10 feet long and 6 inches in diameter, in a stream channel.

Leaching -- The flushing of minerals or pollutants from the soil or other material by the percolation of applied water.

Leaf area index -- a measure of the total area of leaves, twigs, stems, etc., in a forest canopy.

Levee -- An embankment constructed to prevent a river from overflowing (flooding).

Limiting factor -- A requirement such a food, cover, or other physical, chemical or biological factor that is in shortest supply with respect to all resources necessary to sustain life and thus ""limits"" the size or retards production of a population.

Limnology -- The study of lakes, ponds and streams.

Loading -- The influx of pollutants to a selected water body.

Lotic -- Meaning or regarding things in running water.

Macroinvertebrate -- Invertebrates visible to the naked eye, such as insect larvae and crayfish.

Macrophytes -- Aquatic plants that are large enough to be seen with the naked eye.

Mainstem -- The principle channel of a drainage system into which other smaller streams or rivers flow.

Mass movement -- The downslope movement of earth caused by gravity. Includes but is not limited to landslides, rock falls, debris avalanches, and creep. It does not however, include surface erosion by running water. It may be caused by natural erosional processes, or by natural disturbances (e.g., earthquakes or fire events) or human disturbances (e.g., mining or road construction).

Maximum contaminant level (MCL) the highest concentration of a constituent in drinking water permitted under federal and State Safe Drinking Water Act regulations.

Mean annual discharge -- Daily mean discharge averaged over a period of years. Mean annual discharge generally fills a channel to about 1/3 of its bankfull depth.

Mean velocity -- The average cross-sectional velocity of water in a stream channel. Surface values typically are much higher that bottom velocities. May be approximated in the field by multiplying the surface velocity, as determined with a float, times 0.8.

Meander -- The winding of a stream channel, usually in an erodible alluvial valley. A series of sine-generated curves characterized by curved flow and alternating banks and shoals.

Meander amplitude -- The distance between points of maximum curvature of successive meanders of opposite phase in a direction normal to the general course of the meander belt, measured between centerlines of channels.

Meander belt width -- the distance between lines drawn tangential to the extreme limits of fully developed meanders. Not to be confused with meander amplitude.

Meander length -- The lineal distance down valley between two corresponding points of successive meanders of the same phase.

Mesic -- Moderately wet.

Milligrams per liter (mg/L) the weight in milligrams of any substance dissolved in one liter of liquid; nearly the same as parts per million.

Mineralization -- The process whereby concentrations of minerals, such as salts, increase in water, often a natural process resulting from water dissolving minerals found in rocks and soils through which it flows.

Moisture stress -- A condition of physiological stress in a plant caused by lack of water.

Morphology -- The form, shape or structure of a stream or organism.

Multipurpose project -- A project designed to serve more than one purpose. For example, one that provides water for irrigation, recreation, fish and wildlife, and, at the same time, controls floods or generates electric power.

National Pollutant Discharge Elimination System (NPDES) a provision of Section 402 of the federal Clean Water Act of 1972 that established a permitting system for discharges of waste materials to water courses.

Natural flow -- The flow past a specified point on a natural stream that is unaffected by stream diversion, storage, import, export, return flow, or change in use caused by modifications in land use.

Net water demand (net water use) -- The amount of water needed in a water service area to meet all requirements. It is the sum of evapotranspiration of applied water (ETAW) in an area, the irrecoverable losses from the distribution system, and the outflow leaving the service area; does not include reuse of water within a service area (such as reuse of deep-percolated applied water or use of tail water).

Nonpoint source pollution (NPS) -- Pollution that does not originate from a clear or discrete source.

Normalization -- The mathematical manipulation of a variable to allow comparisons with an otherwise different variable.

Normalized demand -- The process of adjusting actual water use in a given year to account for unusual events such as dry weather conditions, government interventions for agriculture, rationing programs, or other irregularities.

Nutrient depletion -- Detrimental changes on a site in the total amount of nutrients and/or their rates of input, uptake, release, movement, transformation, or export.

Off-channel area -- Any relatively calm portion of a stream outside of the main flow.

Off-site enhancement -- The improvement in conditions for fish or wildlife species away from the site of a hydroelectric project that had detrimental effects on fish and/or wildlife, as part or total compensation for those effects.

Outfall -- The mouth or outlet of a river, stream, lake, drain or sewer.

Oxbow -- An abandoned meander in a river or stream, caused by cutoff. Used to describe the U-shaped bend in the river or the land within such a bend of a river.

Pathogens -- Any viruses, bacteria, or fungi that cause disease.

Peat -- Partially decomposed plants and other organic material that build up in poorly drained wetland habitats.

Per capita water use -- The water produced by or introduced into the system of a water supplier divided by the total residential population; normally expressed in gallons per capita per day (gpcd).

Perched ground water -- Ground water supported by a zone of material of low permeability located above an underlying main body of ground water with which it is not hydrostatically connected.

Percolation -- the downward movement of water through the soil or alluvium to a ground water table.

Perennial streams -- Streams which flow continuously.

Perennial yield -- The maximum quantity of water that can be annually withdrawn from a ground water basin over a long period of time (during which water supply conditions approximate average conditions) without developing an overdraft condition. Sometimes referred to as sustained yield.

Permeability -- The capability of soil or other geologic formations to transmit water.

pH -- "The negative logarithm of the molar concentration of hydrogen ion. Or a more simple definition of pH is ""acidity."""

Phytoplankton -- minute plants, usually algae, that live suspended in bodies of water and that drift about because they cannot move by themselves or because they are too small or too weak to swim effectively against a current.

Point Bar -- The convex side of a meander bend that is built up due to sediment deposition.

Point Source (PS) -- (1) A stationary or clearly identifiable source of a large individual water or air pollution emission, generally of an industrial nature. (2) Any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including (but not limited to) pipes, ditches, channels, tunnels, conduits, wells, containers, rolling stock, concentrated animal feeding operations, or vessels. Point source is also legally and more precisely defined in federal regulations. Contrast with Non-Point Source (NPS) Pollution.

Point Source (PS) Pollution -- Pollutants discharged from any identifiable point, including pipes, ditches, channels, sewers, tunnels, and containers of various types. See Non-Point Source (NPS) Pollution.

Pollutant -- (1) Something that pollutes, especially a waste material that contaminates air, soil, or water. (2) Any solute or cause of change in physical properties that renders water unfit for a given use.

Pollution (of water) -- The alteration of the physical, chemical, or biological properties of water by the introduction of any substance into water that adversely affects any beneficial use of water.

Pond -- A body of water smaller than a lake, often artificially formed.

Pool -- A reach of stream that is characterized by deep low velocity water and a smooth surface.

Pool/riffle ratio -- The ratio of surface area or length of pools to the surface area or length of riffles in a given stream reach; frequently expressed as the relative percentage of each category. Used to describe fish habitat rearing quality.

Probability of Exceedence -- The probability that a random flood will exceed a specified magnitude in a given period of time.

Pumped storage project -- A hydroelectric powerplant and reservoir system using an arrangement whereby water released for generating energy during peak load periods is stored and pumped back into the upper reservoir, usually during periods of reduced power demand.

Rapids -- A reach of stream that is characterized by small falls and turbulent high velocity water.

Reach -- A section of stream between two defined points.

Rearing habitat -- Areas in rivers or streams where juvenile fish find food and shelter to live and grow.

Rearing pond -- An artificial impoundment in which juvenile fish are raised prior to release into the natural habitat.

Recharge basin -- A surface facility, often a large pond, used to increase the percolation of surface water into a ground water basin.

Recreational Rivers -- Rivers or sections of rivers that are readily accessible by road or railroad, that may have some development along their shoreline, and that may have undergone some impoundment or diversion in the past.

recreation-day -- Participation in a recreational activity, such as skiing, biking, hiking, fishing, boating, or camping, by one person for any part of a day.

Recycled water -- Urban waste water that becomes suitable, as a result of treatment, for a specific direct beneficial use. See also water recycling.

Reforestation -- The natural or artificial restocking of an area with forest trees.

Regime theory -- A theory of channel formation that applies to streams that make a part of their boundaries from their transported sediment load and a portion of their transported sediment load from their boundaries. Channels are considered in regime or equilibrium when bank erosion and bank formation are equal.

Restoration -- The return of an ecosystem to a close approximation of its condition prior to disturbance.

Return flow -- The portion of withdrawn water not consumed by evapotranspiration or system losses which returns to its source or to another body of water.

Reuse -- The additional use of previously used water.

Riffle -- A reach of stream that is characterized by shallow, fast moving water broken by the presence of rocks and boulders.

Rift -- A shallow or rocky place in a stream, forming either a ford or a rapid.

Riparian area -- An area of land and vegetation adjacent to a stream that has a direct effect on the stream. This includes woodlands, vegetation, and floodplains.

Riparian habitat -- The aquatic and terrestrial habitat adjacent to streams, lakes, estuaries, or other waterways.

Riparian -- Located on the banks of a stream or other body of water.

Riparian vegetation -- The plants that grow adjacent to a wetland area such as a river, stream, reservoir, pond, spring, marsh, bog, meadow, etc., and that rely upon the hydrology of the associated water body.

Ripple -- (1) A specific bedform found in sand bed streams. (2) Undulations or waves on the surface of flowing water.

Riprap -- Rock or other material with a specific mixture of sizes referred to as a "gradation", used to stabilize stream or river banks from erosion or to create habitat features in a stream.

River Channels -- Natural or artificial open conduits which continuously or periodically contain moving water, or which forms a connection between two bodies of water.

River miles -- Miles from the mouth of a river to a specific destination or, for upstream tributaries, from the confluence with the main river to a specific destination.

River Reach -- Any defined length of a river.

River Stage -- The elevation of the water surface at a specified station above some arbitrary zero datum (level).

Riverine -- Relating to, formed by, or resembling a river including tributaries, streams, brooks, etc.

Riverine habitat -- The aquatic habitat within streams and rivers.

Rock -- A naturally-formed mass of minerals.

Rootwad -- The mass of roots associated with a tree adjacent or in a stream that provides refuge for fish and other aquatic life.

Run (in stream or river) -- A reach of stream characterized by fast flowing low turbulence water.

Runoff -- Water that flows over the ground and reaches a stream as a result of rainfall or snowmelt.

Salinity -- The concentration of mineral salts dissolved in water. Salinity may be measured by weight (total dissolved solids), electrical conductivity, or osmotic pressure. Where sea water is known to be the major source of salt, salinity is often used to refer to the concentration of chlorides in the water.

Salinity intrusion -- The movement of salt water into a body of fresh water. It can occur in either surface water or ground water bodies.

Salt marsh -- Saltwater wetlands that occur along many coasts.

Salt-water barrier -- A physical facility or method of operation designed to prevent the intrusion of salt water into a body of fresh water.

Sand -- Small substrate particles, generally referring to particles less than 2 mm in diameter. Sand is larger than silt and smaller than gravel.

Scenic Rivers -- Rivers or sections of rivers that are free of impoundments, with shorelines or watersheds still largely primitive, and shorelines largely undeveloped but accessible in places by roads.

Scour -- The erosive action of running water in streams, which excavates and carries away material from the bed and banks. Scour may occur in both earth and solid rock material and can be classed as general, contraction, or local scour.

Seasonal application efficiency (SAE) the sum of evapotranspiration of applied water and leaching requirement divided by the total applied water, expressed as a percentage: SAE = (ETAW+LR)/AW

Secchi Depth -- A relatively crude measurement of the turbidity (cloudiness) of surface water. The depth at which a Secchi Disc (Disk), which is about 10-12 inches in diameter and on which is a black and white pattern, can no longer be seen.

Secchi Disc -- A circular plate, generally about 10-12 inches (25.4-30.5 cm) in diameter, used to measure the transparency or clarity of water by noting the greatest depth at which it can be visually detected. Its primary use is in the study of lakes.

Secondary treatment -- In sewage, the biological process of reducing suspended, colloidal, and dissolved organic matter in effluent from primary treatment systems. Secondary treatment is usually carried out through the use of trickling filters or by the activated sludge process.

Sediment -- Soil or mineral material transported by water or wind and deposited in streams or other bodies of water.

Sedimentation -- (1) The combined processes of soil erosion, entrainment, transport, deposition, and consolidation. (2) Deposition of sediment.

Seepage -- The gradual movement of a fluid into, through, or from a porous medium.

Sewage -- The liquid waste from domestic, commercial, and industrial establishments.

Silt -- Substrate particles smaller than sand and larger than clay.

Siltation -- The deposition or accumulation of fine soil particles.

Sinuosity -- The ratio of channel length to direct down valley distance. Also may be expressed as the ratio of down valley slope to channel slope.

Slope -- The ratio of the change in elevation over distance.

Slope stability -- The resistance of a natural or artificial slope or other inclined surface to failure by mass movement.

Slough -- A shallow backwater inlet that is commonly exposed at low flow or tide.

Snag -- Any standing dead, partially dead, or defective (cull) tree at least 10 inches in diameter at breast height and at least 6 feet tall. Snags are important riparian habitat features.

Soft Water -- Water that contains low concentrations of metal ions such as calcium and magnesium. This type of water does not precipitate soaps and detergents.

Soluble minerals -- Naturally occurring substances capable of being dissolved.

Spawning -- The depositing and fertilizing of eggs (or roe) by fish and other aquatic life.

Stable Channel -- A stream channel with the right balance of slope, planform and cross-section to transport both the water and sediment load without net long-term bed or bank sediment deposition or erosion throughout the stream segment.

Stone -- Rock or rock fragments used for construction.

Stream -- A general term for a body of flowing water; natural water course containing water at least part of the year. In Hydrology, the term is generally applied to the water flowing in a natural channel as distinct from a canal.

Stream channel -- A long narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

Stream gradient -- A general slope or rate of change in vertical elevation per unit of horizontal distance of the bed, water surface, or energy grade of a stream.

Stream morphology -- The form and structure of streams.

Stream order -- A hydrologic system of stream classification. Each small unbranched tributary is a first order stream. Two first order streams join to make a second order stream. A third order stream has only first and second order tributaries, and so forth.

Stream reach -- An individual segment of stream that has beginning and ending points defined by identifyable features such as where a tributary confluence changes the channel character or order.

Streambank erosion -- The removal of soil from streambanks by flowing water.

Streambank stabilization -- The lining of streambanks with riprap, matting, etc., or other measures intended to control erosion.

Streambed -- (1) The unvegetated portion of a channel boundary below the baseflow level. (2) The channel through which a natural stream of water runs or used to run, as a dry streambed.

Streamflow -- The rate at which water passes a given point in a stream or river, usually expressed in cubic feet per second (cfs).

Substrate -- (1) The composition of a streambed, including either mineral or organic materials. (2) Material that forms an attachment media for organisms.

Subsurface drainage -- Rainfall that is not evapotranspirated or does not become surface runoff.

Superfund list -- A list of the hazardous waste disposal sites most in need of cleanup. The list is updated annually by the U.S. Environmental Protection Agency (EPA) based primarily on how a site scores using the Hazard Ranking System. Also referred to as the National Priorities List (NPL).

Supply augmentation -- Alternative water management programs-such as conjunctive use, water banking, or water project facility expansion-that increase supply.

Surface erosion -- The detachment and transport of soil particles by wind, water, or gravity. Or a groups of processes whereby soil materials are removed by running water, waves and currents, moving ice, or wind.

Surface supply -- water supply from streams, lakes, and reservoirs.

Surface Water -- All waters whose surface is naturally exposed to the atmosphere, for example, rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries, etc., and all springs, wells, or other collectors directly influenced by surface water.

Surplus water -- Developed water supplies in excess of contract entitlement or apportioned water.

Suspended sediment -- Sediment suspended in a fluid by the upward components of turbulent currents, moving ice, or wind.

Suspended Sediment Load -- That portion of a stream's total sediment load which is transported within the body of water and has very little contact the stream bed.

Tailwater -- (1) The area immediately downstream of a reservoir. (2) Applied irrigation water that runs off the end of a field.

Tertiary treatment -- In sewage, the additional treatment of effluent beyond that of secondary treatment to obtain a very high quality of effluent for reuse.

Thalweg -- (1) The lowest thread along the axial part of a valley or stream channel. (2) A subsurface, ground-water stream percolating beneath and in the general direction of a surface stream course or valley. (3) The middle, chief, or deepest part of a navigable channel or waterway.

Tidal flats -- Saltwater wetlands that are characterized by mud or sand and daily tidal fluctuations.

Torrent -- (1) A turbulent, swift-flowing stream. (2) A heavy downpour; a deluge.

Total dissolved solids -- A quantitative measure of the residual minerals dissolved in water that remain after evaporation of a solution. Usually expressed in milligrams per liter. Abbreviation: TDS. See also salinity.

Tractive Force - -The drag on a stream bed or bank caused by passing water which tends to pull soil particles along with the streamflow.

Transpiration -- An essential physiological process in which plant tissues give off water vapor to the atmosphere.

Tributary -- A stream that flows into another stream, river, or lake.

Turbidity -- A measure of the content of suspended matter that interferes with the passage of light through the water or in which visual depth is restricted. Suspended sediments are only one component of turbidity.

Urban runoff -- Storm water from city streets and gutters that usually contains a great deal of litter and organic and bacterial wastes into the sewer systems and receiving waters.

Velocity -- In this concept, the speed of water flowing in a watercourse, such as a river.

Viscosity -- A measure of the resistance of a fluid to flow. For liquids, viscosity increases with decreasing temperature.

Visitor-day -- See recreation-day.

Wash -- (1) To carry, erode, remove, or destroy by the action of moving water. To be carried away, removed, or drawn by the action of water. Removal or erosion of soil by the action of moving water. (2) A deposit of recently eroded debris. (3) Low or marshy ground washed by tidal waters. A stretch of shallow water. (4) (Western United States) The dry bed of a stream, articularly a watercourse associated with an alluvial fan, stream, or river channel. Washes are often associated with arid environments and are characterized by large, high energy discharges with high bed-material load transport. Washes are often intermittent and their beds sparsely vegetated. (5) Turbulence in air or water caused by the motion or action of an oar, propeller, jet, or airfoil.

Washout -- (1) Erosion of a relatively soft surface, such as a roadbed, by a sudden gush of water, as from a downpour or floods. (2) A channel produced by such erosion.

Waste water -- The used water, liquid waste, or drainage from a community, industry, or institution.

Water conservation -- Reduction in applied water due to more efficient water use such as implementation of Urban Best Management Practices or Agricultural Efficient Water Management Practices. The extent to which these actions actually create a savings in water supply depends on how they affect net water use and depletion.

Water demand schedule -- a time distribution of the demand for prescribed quantities of water for specified purposes. It is usually a monthly tabulation of the total quantity of water that a particular water user intends to use during a specified year.

Water Pollution -- Generally, the presence in water of enough harmful or objectionable material to damage the water's quality.

Water quality -- A term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.

Water reclamation as used in this report, includes water recycling, seawater desalting, ground water reclamation, and desalting agricultural brackish water.

Water recycling -- The treatment of urban waste water to a level rendering it suitable for a specific, direct, beneficial use.

Water right -- A legally protected right to take possession of water occurring in a natural waterway and to divert that water for beneficial use.

Water table -- See ground water table.

Water year -- A continuous 12-month period for which hydrologic records are compiled and summarized. In California, it begins on October 1 and ends September 30 of the following year.

Water yield -- The quantity of water derived from a unit area of watershed.

Waterfall -- A sudden, nearly vertical drop in a stream, as it flows over rock.

Watershed -- An area of land thats total surface drainage flows to a single point in a stream.

Watershed management -- The analysis, protection, development, operation or maintenance of the land, vegetation and water resources of a drainage basin for the conservation of all its resources for the benefit of its residents.

Watershed project -- A comprehensive program of structural and nonstructural measures to preserve or restore a water shed to good hydrologic condition. These measures may include detention reservoirs, dikes, channels, contour trenches, terraces, furrows, gully plugs, revegetation, and possibly other practices to reduce flood peaks and sediment production.

Watershed restoration -- Improving current conditions of watersheds to restore degraded fish habitat and provide long-term protection to aquatic and riparian resources.

Weir -- A structure to control water levels in a stream. Depending upon the configuration, weirs can provide a specific "rating" for discharge as a function of the upstream water level.

Weir (fish trap) -- Usually a barrier constructed to catch upstream migrating adult fish.

Wild Rivers -- Rivers or sections of rivers that are free of impoundments and generally inaccessible except by trail, with watersheds or shorelines essentially primitive and waters unpolluted.

Wildfall -- Trees or parts of trees felled by high winds.

Wildlife tree -- A live tree retained to become future snag habitat.

Windthrow -- A tree or trees uprooted or felled by the wind.

Woody debris -- Referring to wood in streams.

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APPENDIX B
Reach Assessment - Physical

Stream _______ Reach _______ Lat/Lon _______________/_______________ Sheet # _______
Date ________ Gage ________ REF? Y N Surveyor ________________

Watershed
Area (sm) ___________
% Imp ______________

Adjacent Land Use (100m)
Wetland ð
Forest ð
Agriculture ð
Parks & Recreation ð
Residential ð
Commercial/Ind. ð
Transportation ð
Utility ð

Riparian Vegetation (30m)
Barren ð
Sedge & Grass ð
BLH ð
Shrub ð
Deciduous ð
Coniferous ð
Invasive ð
Non-Native ð

Cover (%)
Canopy ___________
LWD ___________
Other ____________
____
____

Channel Characteristics
Planform
Bend ð
Cross ð
Straight ð
Profile
Riffle ð
Pool ð
Run ð
Flow Type
Rapid ð
Tranq. ð
Features
Point Bars ð
Mid Bars ð
Shoals ð
Chutes/Backwtr. ð
Snags ð
Control ð
Slope (ft/mi) ___________
Notes: ______________
____
____

Stream Type ___________
CEM Stage ___________

Geometry
Slope
Valley ____________
Reach ____________
Riffle ____________
Pool ____________
Planform
λ ____________
Am ____________
Rc ____________
Pool Depth __________
Pool Width ___________
Riffle Depth ___________
Riffle Width ___________

Protection Characteristics
Type
Unprotected ð
Hardpoints ð
Revetments ð
Bioengineering ð
Grade Control ð
Other
Height ______________
Length ______________
Materials _____________

Bank Characteristics
Height Total @ Riffle (Ft.)
< 4 ð
4 – 8 ð
8 – 12 ð
> 12 ð
Bank Slope
Vertical ð
1:1 ð
1:2 ð
< 1:3 ð
Bank Material
Clay & Silt ð
Sand ð
Gravel ð
Cobbles ð
Bank Condition
Stable ð
Weathering ð
Eroding ð
Advancing ð
Vegetation Types (% Cover)
Barren Soil
Sedge & Grass
Shrubs
Deciduous
Coniferous
Invasive
Non-Native

Erosion Processes
Extent
None (Stable) ð
Bed ð
Toe ð
Upper Bank ð
Whole Bank ð
Predominant Mechanism
None ð
Flow Entrainment ð
Piping ð
Shallow Slide ð
Cantilever ð
Rotational ð
Slab ð
Overbank ð
Other

Substrate
Unknown ð
Clay & Silt ð
Sand ð
Gravel ð
Cobble ð
D50 (mm) __________
D84 (mm) __________
Texture __________

OTHER NOTES / SKETCHES:
(Note Photo Numbers)

APPENDIX B
Reach Assessment - Environmental Characterization

Stream ________ Reach _______ Lat/Lon _____________/_____________ Sheet # _________
Date ________ Gage _______ REF? Y N Surveyor ________________

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
1. Streambank Epifaunal Substrate/ Available Overbank Cover	Greater than 50% of SRH and IRH habitat on existing banks; presence of bars, snags, cut banks, gravel or other stable bank habitat at bankfull stage to allow full colonization potential.	SRH and IRH habitat on 5 to 50% of existing banks; mix of stable streambank habitat but not all types; well-suited for full colonization potential; adequate habitat for maintenance of populations.	Less than 5% useable SRH and IRH habitat; some mix of stable streambank habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 5% useable SRH and IRH habitat; lack of instream habitat diversity is obvious; substrate unstable or lacking.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
2. Instream Substrate Characterization	Mixture of substrate materials, with gravel and cobbles prevalent; sand deposits are firm; several shoals and gravel bars; LWD > 10 percent; embeddedness minimal.	Mixture of sand and gravel with silts at margins; some shoals and gravel bars; emergent vegetation present or not; LWD > 10 percent; gravels and cobbles only slightly embedded.	Primarily sands and silts; few shoals or gravel bars; little emergent vegetation; LWD < 10 percent; gravels are highly embedded.	Shifting fine sands, silts and clays; no shoals or gravel bars; mostly runs; no emergent vegetation; little or no LWD; embeddedness not relevent.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
3. Morphological Diversity and Flow Conditions	Predominantly riffles and pools; few tranquil runs; ratio of distance between riffles divided by width of the stream generally 5 to 10; variety of habitat is key; more than 4 distinct velocity/depth patterns present.	Approximately equal distribution of riffles, pools and runs; distance between riffles divided by the width > 10; more than three distinct velocity/depth patterns present.	Occasional riffle; tranquil runs > 25% of reach; pools associated with LWD; distance between riffles divided by the width of the stream >25; only 1 to 3 distinct velocity/depth patterns present.	Generally all tranquil runs; a few pools near LWD; poor habitat; distance between riffles divided by the width of the stream is a ratio of >25; dominated by one velocity/depth pattern.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
4. Bank Vegetative Diversity and Condition Above Bankfull	More than 90% of the streambank surfaces covered by native vegetation, including trees, understory shrubs, and herbs; vegetative disruption minimal or not evident; almost all plants allowed to grow naturally.	70-90% of the streambank surfaces covered by native vegetation, but one or more class of plants is not well-represented; disruption evident but not affecting full plant growth potential to any great extent.	50-70% of the streambank surfaces covered by vegetation; at least two classes of vegetation present; invasive species present; disruption obvious.	Less than 50% of the streambank surfaces covered by vegetation; only one class of vegetation; invasive species dominant; disruption of streambank vegetation is very high.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
5. Channel Stability (Base Level)	Naturally stable; evidence of incision or bank failure absent or minimal; limited potential for future problems; CEM Level 1 or 5.	Stabilized; Grade control present and evidence of incision or bank failure absent or minimal; some potential for future problems; CEM Level 1, 4, or 5.	Moderately unstable; some entrenchment and/or impending entrenchment; long-term channel stability questionable; impending bank instability; any CEM level.	Unstable; entrenched; active headcuts; impending or active bank failures; any CEM level.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
6. Bank Stability	Banks stable; evidence of erosion or bank failure absent or minimal; little potential for future problems; <5% of bank affected.	Moderately stable; infrequent, small areas of erosion mostly healed over; 5-30% of bank in reach has areas of erosion.	Moderately unstable; 30-60% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "raw" areas frequent along straight sections and bends; obvious bank sloughing; 60-100% of bank has erosional scars.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
7. Riparian Vegetative Zone Width	Width of riparian zone >100 m for at least 90% of bankline; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zone exceeds 30 m for at least 90% of bank length; human activities have impacted zone for less than 10% of banks.	Width of riparian zone less than 30 m for 10 to 50% of bank; human activities have impacted zone for more than 10% of banks.	Width of riparian zone less than 30 m for at least 50% of bank; little or no riparian vegetation due to human activities for at least 10% of banks.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Parameter	Category			
	Optimal	**Suboptimal**	**Marginal**	**Poor**
8. Riparian Management Potential	Existing riparian habitat high quality; preservation of habitat likely with minimal management; affords opportunities for demonstrations and improvements.	Existing riparian habitat only slightly degraded; preservation and/or improvement likely with moderate management effort.	Existing riparian habitat somewhat degraded; preservation and/or improvement possible but would require significant management effort.	Existing riparian habitat degraded; preservation not desirable or attainable; improvement not likely or would require significant and costly management effort.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0